

# Essentials of **Thermal Processing**

Gary Tucker and  
Susan Featherstone



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*Campden BRI, Chipping Campden, UK*

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*Editorial Offices*

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# Preface

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Essentials of Thermal Processing is written by two authors with many years' experience of thermal processing practice, one gained in the northern hemisphere and one in the southern hemisphere. This gives the book a unique appeal. It covers all aspects of thermal processing from its beginnings in 1795 with Nicolas Appert through to modern day computer controlled processing systems and electronic data capture. The intention was to write a book of practical use to students studying food science and technology as well as for their lecturers, but also for individuals in companies and research centres that have a need to understand thermal processing principles.

The book starts with the basic microbiological principles that govern microorganism growth and death, including the use of hurdles to control their growth. When a combination of two or more food preservation factors is used, generally each factor can be used at a slightly lower level. Using more than one food preservation factor or hurdle is termed hurdle technology.

The next chapters take the reader through the different food categories that present their unique challenges for thermal processing. This includes the traditional sector of low acid foods in which the familiar  $F_03$  concept was derived from heat resistance studies originally undertaken by Esty and Meyer in 1922. Low acid foods are a group of foods that do not contain any preservation hurdles to microorganism growth and rely on the heat process to control microorganism numbers in the food and a hermetically sealed package to prevent recontamination.

The two chapters that follow, on acid and high acid foods and on acidified foods, were considered to be sufficiently different that separate chapters were required to describe the categories and the types of thermal processes that are applied. The last of the chapters that deals with a specific food group is on heat preserved chilled foods, which is one of the most rapidly growing sectors in Europe. This includes the ready meal concept and ready-to-eat meat, fish and poultry products. Shelf-life requires refrigerated

storage and is typically up to 10 days when a very mild process is used or it can be extended beyond this with more severe treatments.

The next chapter describes the processing methods that can be used for manufacturing heat preserved foods, which is divided into in-pack or in-line systems, often known as retorts and continuous systems. It does not go into the detail of each commercial system, of which there are many, but describes the operating principles. The main types of retort are described, for example steam, steam-air, water immersion, raining and sprayed water, also included are the in-pack continuous retorts such as hydrostatic and reel & spiral cooker-cooler systems. Equipment choice for a continuous or in-line system depends mostly on the food viscosity and whether the flow behaviour is laminar or turbulent.

Thermal processing of foods has a dual purpose, which is to commercially sterilise the product and to cook it to an acceptable level. The chapter on cooking and process optimisation addresses the challenges of maximising a specific quality attribute without damaging the thermal processing effect on microbial reduction. Examples are given on the different quality parameters appropriate to heat preserved foods and how these can be mathematically analysed with the aim of adjusting processes so that maximum quantities of a nutrient, such as a vitamin, are retained.

Techniques for measuring thermal processes are described in the next chapter together with the process calculation methods used to establish safe times and temperatures. Measurement techniques for in-pack processes include temperature sensors of various types and log reduction methods that can be either microbiological or biochemical. Process calculation techniques are introduced, which allow process conditions to be calculated from the temperature measurements and analysis of deviations to be carried out. Differences in the techniques required for batch (in-pack) and continuous (in-flow) heat processes are described.

Cooling of packs is discussed in the chapter on cooling water. Almost all types of microorganisms can be found in water, and water is most often the vehicle of transmission for these organisms. Inadequate cooling is arguably the single most significant cause of public health issues of the last century from canned foods. Examples of spoilage incidents caused by cooling issues are dealt with in several chapters and so this chapter solely describes the different methods of disinfecting cooling water.

Despite the best efforts to control all aspects of a thermal processing operation, all factories will experience process deviations from time to time. A chapter is dedicated to process deviations and describes methods to assess whether a process deviation has made a critical impact on the commercial sterility or safety of a product. Methods to assess a deviation are many and include calculation methods as well as experimentally recreating the deviation using retort simulators.

Packaging of the product also demanded its own chapter. Understanding packaging options and the way they work together with the product is critical to the success of any food packaging system. The functions of packaging are to contain, protect, preserve, portion, inform, promote and make foods portable. Packaging options for thermally processed foods are many and include metal (mainly tinplate, but some aluminium), glass, cartons and specific plastics (laminates and composites). Primary packaging must be able to hold a hermetic seal, withstand the process temperature, provide a physical barrier, withstand the physical stresses during processing, transport, storage and distribution, and must not react adversely with the food.

Incubation of processed packs is commonplace in the food industry; however, a variety of incubation practices occur, which suggests that there is no standardised approach. The chapter on incubation describes the objectives of incubation together with some recommendations for times and temperatures that different types of microorganism require. It includes suggestions for sample size and methods for interpretation of results.

The penultimate chapter is about the HACCP (Hazard Analysis Critical Control Points) system. HACCP is a tool to assess hazards and establish control systems that focus on prevention rather than relying mainly on end-product testing. Examples are given of CCPs of relevance to thermal processing.

The final chapter presents a different focus for thermal processing in that it deals with environmental aspects and presents a positive case for thermal processing. As a technology for preserving food it can be environmentally beneficial because the goods are stored ambient, thus avoiding the need for refrigeration, and allows agricultural products to be processed close to where they are grown, thus avoiding transportation emissions and forcing crops to grow out of season. An example of a carbon footprint assessment is given in this chapter for a bottled apple juice.

Gary S. Tucker  
Susan Featherstone



The authors during a practical training course session in Cape Town.



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# Glossary of Terms

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<b>Acid Food</b>	A food that has a natural pH of 4.6 or below (in Europe it is common to use pH 4.5 as the upper limit).
<b>Acidified Low-Acid Food</b>	A food that has been treated so as to attain an equilibrium pH of 4.6 (or 4.5 in Europe) or lower after heat processing.
<b>Adverse Conditions</b>	Those conditions that may result in physical damage to and/or contamination of a container or its contents, rendering the food unsuitable for human consumption.
<b>Aerobic</b>	Presence of oxygen.
<b>Anaerobic</b>	Absence of oxygen.
<b>Annealing</b>	Heating process used in tinplate manufacture to soften the steel strip after cold rolling and to impart the required hardness; the process can either be continuous (continuous annealing or CA) or in batches (batch annealing or BA).
<b>Aseptic Processing and Packaging</b>	The filling of a commercially sterile product into sterilised containers followed by hermetical sealing with a sterilised closure in an atmosphere free from microorganisms.
<b>Beads, Beading</b>	Corrugations rolled into can walls to give added strength to the can body.
<b>Bleeders</b>	Small orifices through which steam and other gases escape from the retort throughout the entire heat process.
<b>Broken Heating Curve</b>	A heating curve that shows a distinct change in the rate of heat transfer, such that the curve may be represented by two or more distinct straight lines.

<b>Canned Food</b>	Commercially sterile food in hermetically sealed containers.
<b>Cleaning</b>	The removal of soil, food residues, dirt, grease or other objectionable matter from the external surface of the container and for the purposes of this code may be extended to the removal of rust and other products of corrosion.
<b>Come-up Time</b>	The time, including venting time, which elapses between the introduction of the heating medium into the closed retort and the time when the temperature in the retort reaches the required sterilisation temperatures.
<b>Commercial Sterility</b>	The condition achieved by application of heat, sufficient, alone or in combination with other appropriate treatments, to render the food free from microorganisms capable of growing in the food at normal non-refrigerated conditions at which the food is likely to be held during distribution and storage.
<b>Contamination</b>	The presence of any objectionable material on the surface of a container, or in a food.
<b>Corrosion</b>	Chemical action of dissolving the surface of a metal (e.g. tin in food medium).
<b>Corrosion Accelerator</b>	Chemical species with the ability to accept electrons, which will increase the rate of a corrosion reaction.
<b>Critical Factor</b>	Any property, characteristic, condition, aspect or other parameter, variation of which may affect the scheduled process delivered and thus the commercial sterility of the product. This does <b>not</b> include factors that are controlled by the processor <b>solely</b> for purposes of product appearance, quality and other reasons that are not of public health significance.
<b>Detinning</b>	The process of corrosion, where the internally plain tin coating is slowly dissolved by the food medium; rapid detinning refers to abnormally fast tin dissolution, caused by the presence of corrosion accelerators.

<b>Disinfection</b>	The reduction, without adversely affecting the food, by means of hygienically satisfactory chemical agents and/or physical methods, of the number of microorganisms to a level that will not lead to harmful contamination of food.
<b>Disposal</b>	An action (e.g. incineration, burial, conversion to animal feed, etc.), which will prevent a contaminated product from being sold or distributed for human consumption.
<b>Dr Tinplate</b>	‘Double Reduced’ tinplate where a second rolling is used to reduce steel thickness in order to produce a thinner but stronger product.
<b>Electrolyte</b>	A substance that dissociates into ions when dissolved in a suitable medium; hence a tin-rich electrolyte is used in tinplate manufacture.
<b>Embossing</b>	Use of a die to stamp a product code or manufacturing date into a can end.
<b>Equilibrium pH</b>	The pH of the macerated heat processed food product.
<b>Fermented Food</b>	A food preserved by the growth of acid-producing microorganisms in the food, which lowers the pH to 4.6 (4.5 in Europe) or less.
<b>Fill Temperature</b>	Temperature at which the food is filled into the container.
<b>Fill Weight</b>	The weight of the product particulates before processing, excluding the weight of the container or covering liquid.
<b>Filler</b>	Machine used to automatically fill a container with the desired weight or volume of food.
<b>Flexible Container</b>	A container where the shape or contours of the filled, sealed container are affected by the enclosed product.
<b>Food Acids</b>	Organic acids, naturally occurring in foods, especially in fruits and vegetables; also used to impart flavour and to modify the pH of foods.

<b>Headspace</b>	Space left in the top of the container after filling and end sealing, in order to allow for product expansion during thermal processing/the volume in a container not occupied by the food.
<b>Heating Curve</b>	A graphical representation of the rate of temperature change in the food throughout the heat process; this is usually plotted on semi-log graph paper so that the temperature on an inverted log scale is plotted against time on a linear scale.
<b>Hermetically Sealed Container</b>	A container that is designed and intended to be secure against the entry of microorganisms and to maintain the commercial sterility of its contents during and after processing (e.g. tinplate or aluminium can, glass jar, or pouch).
<b>Incubation Tests</b>	Tests in which the heat processed product is kept at a specific temperature for a specified period of time in order to determine if outgrowth of microorganisms occurs under these conditions.
<b>Initial Temperature</b>	The temperature of the contents of the coldest container to be processed at the time the sterilising cycle begins, as specified in the scheduled process.
<b>Inject Coding</b>	Use of an ink jet to print a product code or manufacturing date on the package.
<b><math>K_w</math></b>	$K_w$ is an equilibrium constant for the chemical reaction that describes the ionisation of water. It is referred to as the ionisation constant or the ionic product. It has the units $\text{mol}^2 \text{dm}^{-6}$ .
<b>Lacquers</b>	Inert organic coatings used to give additional protection to tinplate; usually applied in liquid form and 'cured' at high temperatures.
<b>Low-Acid Food</b>	Any food (other than alcoholic beverages) with a finished equilibrium pH greater than 4.6 (4.5 in Europe) and a water activity greater than 0.85, excluding tomatoes and tomato products having a finished equilibrium pH less than 4.7.

<b>Nesting</b>	Containers that fit within one another when stacked.
<b>Pack Testing</b>	Storage and regular sampling of canned foods under controlled temperature conditions to determine internal corrosion characteristics and potential shelf-life.
<b>Packing Medium</b>	The liquid or other medium in which the low-acid or acidified product is packed.
<b>pH</b>	A measure of acidity.
<b>Plain Cans</b>	Cans made from tinplate without any additional lacquer coating.
<b>Potable Water</b>	Water fit for human consumption.
<b>Process Authority</b>	The person or organisation that scientifically establishes thermal processes for low acid canned foods or processing requirements for acidified foods. The processes are based on scientifically obtained data relating to heat or acid resistance of public health and spoilage bacteria and/or upon data pertaining to heat penetration in canned foods. The process authority must have expert scientific knowledge of thermal and/or acidification processing requirements and have adequate experience and facilities for making such determinations.
<b>Process Temperature</b>	The calculated temperature at a particular time (process time) for which a specific container size and food product need to be heated in order to achieve commercial sterility.
<b>Process Time</b>	The calculated time at a particular temperature (process temperature) for which a specific container size and food product need to be heated in order to achieve commercial sterility.
<b>Recanning</b>	The transfer and sealing of a product into a new hermetically sealable container followed by a scheduled process.
<b>Reconditioning</b>	The cleaning of sound containers and may include disinfection.

<b>Reducing Environment</b>	Conditions expected inside a plain processed food container, whereby the contents are protected from oxidative reactions such as colour change.
<b>Reprocessing</b>	The treatment of a canned food in its original container recovered in a salvage operation followed by a scheduled process.
<b>Retort</b>	A pressure vessel designed for thermal processing of food packed in hermetically sealed containers.
<b>Rigid Container</b>	A container whereby the shape or contours of the filled and sealed container are neither affected by the enclosed product nor deformed by an external mechanical pressure of up to $0.7\text{ kg/cm}^2$ (10 psig) (i.e. normal firm finger pressure).
<b>Sacrificial Anode</b>	A metal that slowly dissolves in a corrosion reaction and, in so doing, protects a second metal from corrosion (e.g. tin behaving as the sacrificial anode to protect the coupled steel base).
<b>Salvage</b>	Any appropriate process or procedure by which food is recovered from a suspect lot of canned food and by which its safety and fitness for consumption is ensured.
<b>Scheduled Process</b>	The thermal process chosen by the processor for a given product and container size to achieve at least commercial sterility.
<b>Seals</b>	Those parts (of a semi-rigid container and lid or flexible container) that are fused together in order to close the container.
<b>Semi-Rigid Container</b>	A container whereby the shape or contours of the filled, sealed container are not affected by the enclosed product under normal atmospheric temperature and pressure but can be deformed by an external mechanical pressure of less than $0.7\text{ kg/cm}^2$ (10 psig) (i.e. normal firm finger pressure).
<b>Shelf-Life</b>	The expected acceptable commercial life of any canned food.

<b>Sidestripe</b>	A thin band of lacquer designed to protect the weld of a can body from corrosion.
<b>Steam Exhausting</b>	Passing filled containers through a tunnel of steam, prior to sealing, to assist in oxygen removal from the product and headspace.
<b>Sterilisation Temperature</b>	The temperature maintained throughout the thermal process as specified in the scheduled process.
<b>Sterilisation Time</b>	The time between the moment when sterilisation temperature is achieved and the moment when cooling started.
<b>Sterilising Value (<math>F_0</math>)</b>	The number of minutes at a reference temperature of 250°F Fahrenheit (121.1°C) required to kill a known population of microorganisms with a z value of 18°F (10°C).
<b>Sulphide Staining</b>	Where naturally occurring sulphur compounds in foods react with the tinplate surface to form a purple-black stain of tin sulphide or black iron sulphide.
<b>Suspect Lot</b>	A group of containers that is suspected of being contaminated as a result of exposure to adverse conditions and may include a part of, the whole of, or a number of code lots.
<b>Thermal Process</b>	The application of heat to food, either before or after sealing in a hermetically sealed container, for a period of time and at a temperature scientifically determined to achieve a condition of commercial sterility.
<b>Venting</b>	The thorough removal of the air from steam retorts by steam prior to a scheduled process.
<b>Water Activity (<math>a_w</math>)</b>	A measure of the free moisture in a product. It is the quotient of the water vapour pressure of the substance divided by the vapour pressure of pure water at the same temperature.





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# **1 Microbiology of Heat Preserved Foods**

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Microbiology refers to the study of life and organisms that are too small to be seen with the naked eye. This includes eukaryotes such as fungi, and prokaryotes such as bacteria. Microbiology is researched actively, and the field is advancing continually. We have probably only studied and understand a very small percentage of all of the microorganisms on Earth. Although microorganisms were first observed over 300 years ago, the science of microbiology is in its infancy.

## **1.1 A BRIEF HISTORY OF THE SCIENCE AND TECHNOLOGY OF THERMAL PROCESSING**

The early Greeks believed in ‘spontaneous generation’ (that living things could originate from non-living matter). Although Aristotle discarded this notion, he still believed that animals could arise spontaneously from other unlike organisms or from soil. His influence regarding this concept of spontaneous generation was still felt as late as the seventeenth century. Towards the end of the seventeenth century, a chain of observations, experiments and arguments began that disproved the belief that life could be generated from non-life. Microbiology, as a science, can be said to have begun with the development of the microscope. In the mid-seventeenth century, although not the inventor of the microscope, Antonie van Leeuwenhoek (1632–1723) (Fig. 1.1), a Dutch draper, ground his own lenses and made small microscopes that could magnify up to 500 times. He had exceptional attention to detail and was the first to provide proper descriptions of his observations, which included protozoans from the guts of animals and bacteria from teeth scrapings. His descriptions and drawings were



**Fig. 1.1** Antonie van Leeuwenhoek, painting by Jan Verkolje.

excellent and he conveyed his findings in a series of letters to the British Royal Society during the mid-1670s. Although the observation of his ‘animalcules’ stimulated much interest, it remained as an oddity until the eighteenth century.

In 1795, the French government offered a cash award of 12 000 francs to any inventor who could devise a cheap and effective method of preserving large amounts of food. The larger armies of the period required increased, regular supplies of quality food. Limited food availability was among the factors limiting military campaigns. After many years of experimentation, French confectioner and brewer, Nicolas Appert (1752–1841) (Fig. 1.2), developed a method of sealing and heating food in glass jars, where the food did not spoil unless the seals leaked. He tested his experiments in 1795 and in 1904 founded a cannery at Massy, following successful public tests of his bottled foods aboard ships at Brest.

In 1810, Appert published his findings in a book entitled *Le Livre de Tous les Ménages ou L’Art de Conserver Pendant Plusieurs Années Toutes les Substances Animales et Végétales* (The Book for All Households or The Art of Preserving Animal and Vegetable



**Fig. 1.2** Nicolas Appert, drawing by unknown.

Substances for Many Years), and was awarded his cash prize. In his book he described the following steps in the canning process:

- Enclose, in bottles, the food to be preserved.
- Cork the bottle carefully.
- Submit the bottles to the action of boiling water for various lengths of time, depending on the food.
- Remove the bottles and allow them to cool.

The reason for lack of spoilage was unknown at the time, since it would be another 50 years before Louis Pasteur demonstrated the role of microorganisms in food spoilage.

There were many other people working on methods of food preservation at the time, including the Englishmen, Donkin and Saddington (who, in 1807, were awarded 5 guineas for their method of using heat to preserve fruits without using sugar).

Glass jars were soon largely replaced in commercial canneries with cylindrical tin or wrought-iron canisters (later shortened to



**Fig. 1.3** Louis Pasteur, painting by A. Edelfeldt (1885).

‘cans’), following the work of Peter Durand in 1810. The cans were cheaper and quicker to make, and much less fragile than glass jars. The firm of Donkin and Hall manufactured large quantities of ‘canisters’, some of which were taken on expeditions to Baffin Bay in 1814 and on Arctic explorations in 1815.

Appert’s book was translated into many languages, with an English version published in 1811, followed by a second edition in 1812 (Appert, 1810). Appert continued developing his canning processes and published a fourth edition in 1831, when he was almost 80 years old.

Many scientific and technological advances occurred over the next few decades. In 1859, Louis Pasteur (Fig. 1.3) did some work on ‘spontaneous generation’. Pasteur first drew the necks of glass flasks out so that they remained open to the air, but were bent so that air could only enter by a curved path. He added broth and boiled it to destroy contaminating microorganisms. The flasks were then incubated and observed for months. The logic was that if there were microorganisms in the air that could contaminate the sterile broth, these microorganisms would be trapped on the sides of the thin glass necks before they reached the sterile broth. No growth occurred, so he tilted the flasks to allow the broth to reach the valley in the neck and back again. After another incubation period the broth turned



**Fig. 1.4** Joseph Lister, painting by unknown.

murky. This proved his theory that there were microorganisms in the air that could spoil the broth. Pasteur made several other discoveries including vaccinations for several diseases, such as rabies (a viral vaccine). In 1862 he did a series of experiments that proved that heat treating beverages such as milk, beer and wine could stop them from spoiling. This process became known as pasteurisation.

Joseph Lister (1827–1912) was an English surgeon who made the important development of antiseptic surgical practice for medicine and microbiology (Fig. 1.4). Lister searched for a way to keep bacteria out of wounds and incisions made by surgeons, as death from sepsis was frequent at the time. He read a paper by Louis Pasteur that described the growth of anaerobic bacteria and suggested killing them by heat, filtering or with chemicals. Carbolic acid (phenol) was known to deodorise sewage, so Lister soaked surgical dressings, and sprayed carbolic acid into the air of operating theatres. The protected wounds did not become infected and the patients recovered quickly. The success of this technique was so remarkable that aseptic surgical practice was soon established worldwide.

Robert Koch (1843–1910) isolated the *Bacillus* bacteria responsible for tuberculosis and the one for anthrax. He also isolated the bacteria responsible for cholera, *Vibrio cholera*. In his work with anthrax he noticed that when the bacteria were exposed to

unfavourable conditions, they went into a dormant state, forming internal spores that could survive for extended periods in the soil, causing outbreaks of the disease at opportune times. More of Koch's contributions to microbiology were in the areas of culturing bacteria and examining them. He developed solid culture media by adding gelatine and other solidifying agents to liquid media in order to obtain isolated growths of microorganisms. These isolated growths were called 'colonies' and were found to contain millions of individual microorganisms packed tightly together. He noted that the colonies were visible to the naked eye, whereas the individual cells were not. Koch also found that, by adding dyes to microorganisms smeared onto a glass slide, individual cells could be seen more clearly with a microscope.

In about 1860, Isaac Solomon, a canner in Baltimore in the USA, added calcium chloride to the cooking water enabling it to 'boil' at 116°C instead of 100°C, and thus reducing the cooking times from in the region of 6 hours to about 30 minutes.

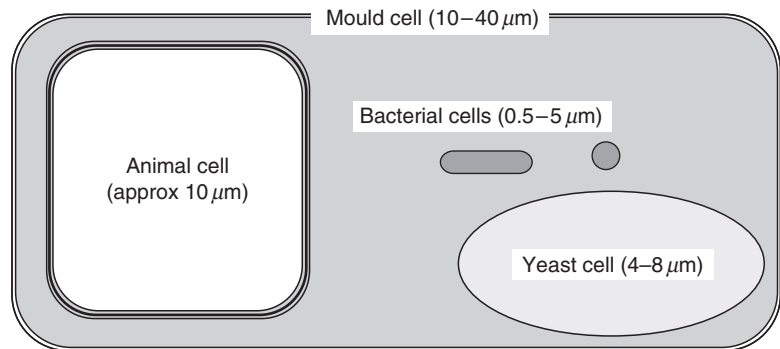
In the twentieth and twenty-first centuries, our knowledge and understanding of microbiology has increased exponentially. The development of stronger microscopes, better aseptic techniques, computers, biotechnology tools and sophisticated analytical instruments have all contributed to unravelling the many conundrums caused by microorganisms in the field of medicine and food science. Two of the most important advances were the invention of the retort by A.K. Shriver in 1875, and publication of time temperature requirements of canned foods by Underwood and Prescott. William Lyman Underwood was a canner who wanted to understand what caused canned food spoilage (Fig. 1.5). Together with Samuel Cate Prescott, they studied many cases of food spoilage over many years. They demonstrated that spoilage could be caused by inoculation and that the proper temperature time combinations could prevent spoilage. They showed that bacteria were the causative agents of canned food spoilage, the importance of heat penetration in processing canned foods, the importance of cooling of canned foods and they were also the first to recommend incubation of canned foods. The significance of their work cannot be overemphasised; canning passed from an individual skill to a scientific discipline.

## **1.2 FOOD MICROBIOLOGY**

Ever since man has been gathering food, he has had the problem of preserving it. Very soon after food is harvested or slaughtered it starts deteriorating. Food microbiology is concerned with the



**Fig. 1.5** Underwood and Prescott (courtesy of the MIT Museum).



**Fig. 1.6** Diagram showing relative size of bacteria, yeast and mould.

organisms that cause loss of food quality and safety, as well as those organisms that help to preserve the food and keep other organisms at bay (Frazier, 1958; Kay, 1992). The microorganisms of importance in the food industry are fungi and bacteria. Figure 1.6 shows the size of animal cells relative to mould, yeast and bacteria.

### 1.2.1 Fungi

Fungi are an interesting group of eukaryotic organisms that are neither plant nor animal. Like plants they possess a cell wall and can reproduce both asexually and sexually. But like animals they



do not contain chlorophyll and are heterotrophic organisms. The majority of fungal species grow as multicellular filaments, called hyphae, forming a mycelium (mould). Some fungal species also grow as single cells (yeasts). Sexual and asexual reproduction of the fungi is commonly via spores, often produced on specialised structures or in fruiting bodies. The discipline of biology devoted to the study of fungi is known as mycology.

The use of fungi for food preservation is extensive. Yeasts are required for fermentation of beer, wine and bread, and moulds are used in the production of cheese and soy sauce. Some fungi are also used for antibiotic production. Many fungi produce biologically active compounds, several of which are toxic and are therefore called mycotoxins. Of particular relevance to humans are those mycotoxins that are produced by moulds causing food spoilage, an example being the aflatoxins, which are liver toxins and carcinogenic metabolites.

#### 1.2.1.1 *Moulds*

Moulds include all species of microscopic fungi that grow in the form of multicellular filaments, the hyphae. The individual mould structures, single hypha or spores, can only be seen under a microscope. The term 'mould' describes the mass of mycelium, made up from many hyphae, that is visible as a colony with the naked eye. They are widely distributed in Nature, in both the soil and in the air. Under suitable conditions (e.g. moisture, temperature and oxygen), they can grow on almost any food source. They can grow at many extremes, highly acidic or very salty, low temperature and on carbon sources that are not generally considered to be food (e.g. ceilings, walls, books). One important feature of mould metabolism that is important to note is the ability to consume acids, thus raising the pH of a foodstuff, and potentially allowing micro-organisms to grow that were otherwise inhibited by the low pH. All moulds are aerobic, but some can grow in relatively low oxygen concentrations. Generally, moulds are not very heat resistant, but some spores can survive heating to about 90°C for a few minutes. Mature spores (ones that have had several days to mature) are generally more resistant. These present problems for fruit canning where the process severity is limited by the breakdown in fruit texture caused by heat.

Food safety risks from mould contamination are limited to mycotoxins, which are secondary metabolites produced by moulds. The name 'mycotoxin' comes from the Greek words, mykes (mould) and toxicum (poison). There are many known types of mycotoxins and they can contaminate a wide variety of food and animal feeds. Examples of common mycotoxins include Aflatoxin, Ochratoxin

A, Patulin, Fusarin, Fumonisin, deoxynivalenol (DON) and Zea-ralenone. Mycotoxins are not essential to maintaining the life of the mould in a primary way (i.e. obtaining energy or synthesising structural components, etc.). They are chemical compounds that give the mould a competitive advantage over other moulds or bacterial species in their environment. They are almost all cytotoxic, disrupting various cellular structures such as membranes and interfering with vital cellular processes such as RNA and DNA synthesis.

The consumption of mycotoxin contaminated food is related to several acute and chronic diseases in humans and animals. An example of a serious food related problem caused directly by mycotoxins occurred in 1960, where 100 000 turkey poultts died after eating peanut meal that was contaminated with aflatoxins. Aflatoxins are a group of toxins produced by *Aspergillus* spp that have a similar structure and form highly oxygenated heterocyclic compounds. There are four major aflatoxins: B1, B2, G1 and G2. Aflatoxins have a potent carcinogenic effect. Aflatoxins occur in crops (most commonly corn, peanuts and cottonseed) post harvesting if the moisture levels in the foodstuff is allowed to exceed the critical values for mould growth. They can also be found in milk, cheese and eggs, if the animals are fed contaminated feed.

Patulin is a mycotoxin that is produced by certain species of *Penicillium*, *Aspergillus* and *Byssoschylamys* moulds. The moulds that produce patulin grow on a variety of foods, including fruit (e.g. apples, grapes and pears), vegetables, grains (e.g. flour and malt) and cheese. However, given the nature of the food (e.g. pH, protein amino acid composition, etc.), the manufacturing processes, or consumption practices for many foods, patulin does not appear to pose a public safety concern, with the exception of apple juice. Patulin is relatively stable in acid solutions, but is susceptible to alkaline hydrolysis and is destroyed by fermentation, which means it is not found in either alcoholic fruit beverages or vinegar produced by fruit juices, but will survive a pasteurisation process.

Ocratoxin (sp) A is a mycotoxin produced by *Apergillus ochraceus* and a few other moulds, for example *Penicillium viridicatum* and *Penicillium verrucosum*. It has both antibiotic and toxic (carcinogenic, teratogenic and nephrotoxic) properties.

### 1.2.1.2 Yeasts

Yeasts are heterotrophs that use organic compounds as a source of energy and do not require sunlight to grow. The main source of carbon is from hexose sugars such as glucose and fructose, or disaccharides such as sucrose and maltose, although some species

can metabolise pentose sugars (e.g. ribose), alcohols and organic acids. Yeasts are either obligate aerobes or are facultative anaerobes. Unlike bacteria, there are no known yeast species that grow only anaerobically (obligate anaerobes). Yeasts grow best in a neutral or slightly acidic pH environment. They will grow over a temperature range of 10 to 37°C, with an optimal temperature range of 30 to 37°C, depending on the type of species. Above 37°C, yeast cells become stressed and above 50°C most will die. The cells can survive freezing under certain conditions, with viability decreasing over time. Although yeasts are substantially larger than bacteria they are only visible with the naked eye as colonies, and must be viewed through a microscope.

Although they are very useful in the food industry – they are used for bread, beer and wine manufacture and as a vitamin source – they can spoil some food because they have certain traits that enable them to opportunistically infect and spoil food. These are the ability to grow at low pH (or in high acid conditions below pH 4.0) and the ability to grow at high sugar concentrations (or low water activity down to 0.62  $a_w$ ). These characteristics make yeasts ideal candidates for food spoilage in fruit products (e.g. juices, canned fruits and jams) and other high acid foods such as pickles and yoghurt. Yeasts actively produce carbon dioxide gas in their metabolism, which can cause destructive spoilage (especially in products in sealed containers).

### 1.2.2 Bacteria

Bacteria are a large group of prokaryotic, unicellular microorganisms that are very important to the food processor. They are typically only a few micrometres ( $10^{-6}$ m) in length (Fig. 1.6). In contrast to higher organisms, bacteria exhibit an extremely wide variety of metabolic types, as highlighted in Table 1.1.

Bacteria are ubiquitous; growing in soil, acidic hot springs, radioactive waste, water, deep in the Earth's crust, as well as on organic matter and the bodies of living plants and animals.

Most bacteria are harmless to humans, but some can secrete enzymes that can cause changes in food or toxins that can contaminate food. Intimate knowledge of food poisoning and food spoilage organisms is critical to the food processor, as this knowledge can assist in controlling microbial outbreaks and contamination.

Microscopic examination is a quick tool used to identify bacteria. Characteristics such as their shape, size, aggregation, structure and staining reactions (e.g. Gram stain) all are typical to certain

**Table 1.1** Nutritional types in bacterial metabolism.

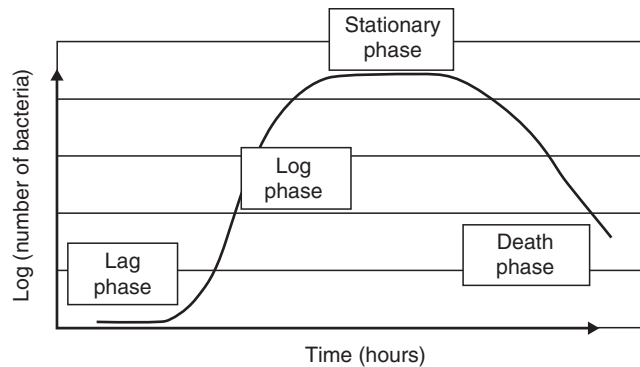
Nutritional type	Energy source	Carbon source	Examples
Phototrophs	Sunlight	Organic compounds (photoheterotrophs) or carbon fixation (photoautotrophs)	<i>Cyanobacteria</i> , Green sulphur bacteria, <i>Chloroflexi</i> or Purple bacteria
Lithotrophs	Inorganic compounds	Organic compounds (lithoheterotrophs) or carbon fixation (lithoautotrophs)	<i>Thermodesulfobacteria</i> , <i>Hydrogenophilaceae</i> or <i>Nitrospirae</i>
Organotrophs	Organic compounds	Organic compounds (chemoheterotrophs) or carbon fixation (chemoautotrophs)	<i>Bacillus</i> , <i>Clostridium</i> or <i>Enterobacteriaceae</i>

groups of bacteria. Colonies of bacteria comprise millions of cells and are visible with the naked eye.

Bacteria are found in a wide range of shapes, such as spheres, rods and spirals. Certain species of bacteria are motile, propelling themselves using tails called flagellae. Some bacteria produce external slime (or capsules). Some species of bacteria, such as *Bacillus* and *Clostridium*, can form (internal) highly resistant, dormant structures called endospores. Endospores have a central core of cytoplasm containing DNA and ribosomes, which is protected by an impermeable and rigid coat. They show no detectable metabolism and can survive extreme physical and chemical stresses, such as high levels of UV light, gamma radiation, detergents, disinfectants, heat, pressure and desiccation. In this dormant state, bacteria may remain viable for thousands of years, and can even survive exposure to the vacuum and radiation in space. Endospore-forming bacteria are often implicated in diseases and food poisoning, for example anthrax can be contracted by the inhalation of *Bacillus anthracis* endospores, and botulism can be caused by the consumption of the toxin formed by *Clostridium botulinum* endospore outgrowth in canned food.

#### 1.2.2.1 Growth and reproduction of bacteria

Unlike multicellular organisms, bacteria grow to a fixed size and then reproduce through binary fission (a form of asexual reproduction). Under optimal conditions, bacteria can grow and divide extremely rapidly, and bacterial populations can double as quickly



**Fig. 1.7** Growth rate versus time for the various phases of microbial growth.

as every 10 minutes. In this sort of cell division, two identical clone daughter cells are produced.

A typical growth cycle of bacteria is shown graphically in Fig. 1.7. When introduced into a food, the bacteria require some time to adapt to their new surroundings, during which very little cell multiplication takes place (called a lag phase). Once adapted, cell division occurs at an exponential rate (called the log phase), during which time cell numbers increase dramatically. When certain factors become limiting (such as the food source and space) and the amount of waste products produced by the bacteria build-up, cell division slows down again (called the stationary phase) and eventually cells stop dividing, resulting in their death. The time taken for the population of cells to double is known as the generation time. The generation time of a microorganism will depend on the type and its environment. Typically, under favourable conditions bacteria have a generation time of 20 to 30 minutes. Thus, every hour, the population can double two or three times over (Table 1.2).

If binary fission growth is not limited, the population can amount to a staggering figure of over  $2.8 \times 10^{15}$  in just 24 hours. Fortunately, while rapid growth of bacteria and other microorganisms is a reality there are always factors that do limit the growth, so these sorts of numbers do not occur.

Understanding the growth of microorganisms is important because they can multiply very rapidly. Once accustomed to their environment, in the presence of optimal growth conditions, if the numbers are high to start with then adaptation is quicker and numbers will increase faster and spoilage will occur sooner.

**Table 1.2** Theoretical increase in population of bacteria under ideal conditions.

Time	Theoretical number of bacteria	
Start	1	$1.0 \times 10^0$
30 min	2	$2.0 \times 10^0$
1 h	4	$4.0 \times 10^0$
2 h	16	$1.6 \times 10^1$
5 h	1024	$1.0 \times 10^3$
6 h	4096	$4.1 \times 10^3$
8 h	65 536	$6.5 \times 10^4$
12 h	1 677 216	$1.6 \times 10^7$
24 h	281 474 976 710 656	$2.8 \times 10^{15}$

### 1.3 FACTORS THAT AFFECT THE GROWTH OF MICROORGANISMS

There are a number of factors that affect microbial growth and it is important that these are understood in order to be able to control the microorganism numbers (Prescott *et al.*, 1996). In the list below, the first six are called intrinsic factors and are Nature's ways of protecting foods from microorganisms, and the last three are called extrinsic factors and are properties of the storage environment that foods are kept in:

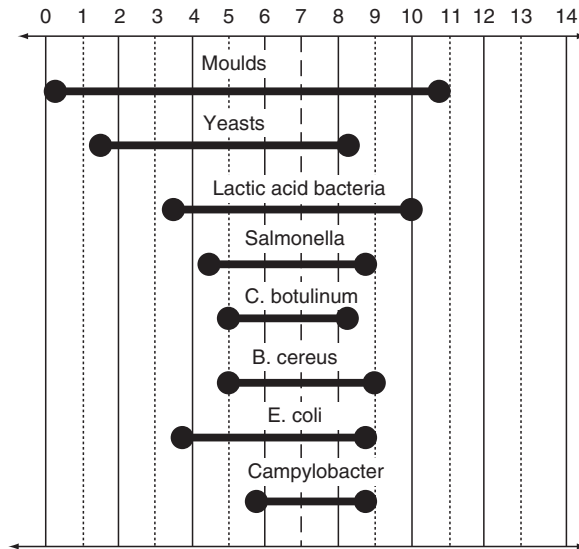
- (i) pH;
- (ii) moisture;
- (iii) nutrients;
- (iv) redox potential;
- (v) antimicrobial resistance;
- (vi) biological structures;
- (vii) relative humidity;
- (viii) oxygen content/gases in the environment;
- (ix) temperature.

#### 1.3.1 pH

The pH is a measure of the solution's acidity and refers to the hydrogen ion concentration of a solution. It is defined as the negative logarithm of the concentration of  $H^+$  ions, as given in Equation 1.1:

$$pH = -\log_{10}[H^+] \quad (1.1)$$

where  $[H^+]$  is the concentration of  $H^+$  ions in moles per litre.



**Fig. 1.8** pH growth ranges of microorganisms.

The pH scale ranges from 0 to 14, with 7 being the pH of pure water and is regarded as neutral. Less than 7 is acidic and greater than 7 is alkaline. Most microorganisms grow best at neutral pH and only a few are able to grow  $\text{pH} < 4.0$ . Most foods are acidic ( $\text{pH}$  3–7). Chapters 4 and 5 deal with acid and acidified foods in greater detail, as well as the theory of acidity measurement using pH.

Bacteria are more selective about their pH requirements than yeasts and moulds. The fact that pH can limit microbial growth is one of the basic principles of food preservation and has been used for thousands of years. For example, fermentation and pickling have been used to extend the shelf-life of food products by lowering the pH. The fact that no known spore-forming pathogenic bacteria can grow at  $\text{pH} < 4.6$  is the basis for the food sterilisation principle for low acid and acid foods. Figure 1.8 gives some examples of the pH growth ranges of various microorganisms.

Although each microorganism will have an optimum pH, most can grow over a fairly wide range. The kind of acid used to change the pH will also affect the ability of microorganisms to grow (refer to Chapter 5 for details). It is important to note that on either side of the optimum pH the lag phase of the growth curve will be extended while the microorganism is adapting to the conditions, so a delay in growth does not necessarily mean no growth.

Some microorganisms can survive in adverse pH conditions, but not exhibit growth. Other microorganisms can alter the pH of

a substrate (due to the metabolites they produce). This can cause other microorganisms to thrive, which were previously only just surviving.

Many microorganisms produce acids and lower the pH of a substrate (this is the basis for preserving food by pickling). It is important to realise that the pH can also be increased by the growth of certain microorganisms. For example, the pH of a substrate can be raised when *Clostridium acetobutylicum* metabolises butyric acid and *Enterobacter aerogenes* metabolises pyruvic acid during growth. This pH increase can allow other organisms that are kept dormant by the lower pH to grow.

Other environmental factors also interact with pH, for example the pH of a substrate increases as the temperature increases (albeit slightly).

### 1.3.2 Moisture

Microorganisms cannot grow in a water-free environment, because enzyme activity is absent, and most chemical reactions are greatly slowed down. Fresh vegetables, fruit, meat and fish naturally have a high moisture content, which averages about 80%. This effect is used in drying, which is one of the oldest methods of food preservation. Drying reduces the availability of the moisture, thereby limiting the numbers and types of microorganisms that can grow and reduces the rate at which they can do so. A measure of this parameter is called *water activity* and is defined by the ratio of the water vapour pressure in the food substrate to the vapour pressure of pure water at the same temperature and is denoted by the term  $a_w$ , as given in Equation 1.2:

$$a_w = p/p_o \quad (1.2)$$

where  $p$  is the vapour pressure of the solution (food),  $Pa$ , and  $p_o$  is the vapour pressure of pure water,  $Pa$ .

Water activity is a measure of the water that is available to the microorganisms. Pure water has a water activity of 1.0, while most fresh foods have a water activity of about 0.99 to 0.98. The growth of most microorganisms is confined to the  $a_w$  range above 0.90, but some organisms that are of great importance in food preservation and food spoilage can grow at lower levels. These are termed halophiles, xerophiles and osmophiles. Halophiles are unable to grow in environments with no salt (NaCl) and often require substantial amounts of salt to grow. Xerophiles are



organisms that can grow in relatively dry (low  $a_w$ ) conditions. Osmophiles can grow in environments where the osmotic pressure is high, for example in high sugar solution (e.g. jams and glacéed fruit).

In general, bacteria require an environment with a higher  $a_w$  than yeasts and moulds. Most spoilage bacteria cannot grow at  $a_w < 0.90$ . The minimum  $a_w$  value for a halophilic bacterial growth is 0.75. *C. botulinum* has a minimum growth level of  $a_w$  0.94, whereas the salt tolerant organism *Staphylococcus aureus* can grow at  $a_w$  values as low as 0.84.

Fungi (yeasts and moulds) are more resistant to low moisture conditions than bacteria. Most spoilage moulds cannot grow at  $a_w < 0.80$ , although the minimum  $a_w$  for xerophilic mould growth is 0.61. Most spoilage yeasts can grow in a minimum of  $a_w$  0.88, although osmophilic yeasts can grow at  $a_w$  as low as 0.61.

### 1.3.3 Nutrients

To be able to grow and function normally, microorganisms require water, a source of energy, a source of nitrogen, vitamins and other growth factors and minerals. Food is made up from water, proteins, fats, carbohydrates and a host of vitamins and minerals. Some microorganisms are better suited to food spoilage using specific nutrients than others.

Carbohydrates are organic compounds that contain carbon, oxygen and hydrogen. They can be simple sugars or complex molecules. They have the general formula  $C_n(H_2O)_n$ . Food carbohydrates include monosaccharides (e.g. glucose), disaccharides (e.g. lactose, sucrose) and polysaccharides (e.g. dextrins, starches, celluloses, pectins). Monosaccharides and disaccharides are also referred to as sugars. They are readily digested and metabolised by the human body to supply energy, but can also be easily metabolised (fermented) by microorganisms.

Fats are the second most important source of energy in the microorganism's diet, after carbohydrates. The yield of energy from fats is more efficient, with fats yielding more than double the amount of energy as an equivalent amount of carbohydrate. They are also an essential part of the diet, and are utilised in membrane, cell, tissue and organ structures. Fats or oils (triglycerides) are a group of naturally occurring organic compounds (esters) comprised of three molecules of fatty acids covalently bonded to one molecule of glycerol. The properties of the fat are determined by the type and length of fatty acids that are bonded to the glycerol molecule.

Fats are designated as saturated or unsaturated, depending on whether the chemical bonds between the carbon atoms of the fatty acid molecule contain all the hydrogen atoms they are capable of holding (saturated), or whether they have capacity for additional hydrogen atoms (unsaturated). Saturated fats generally are solid at room temperature, and unsaturated and polyunsaturated fats are liquids. Unsaturated fats may be converted to saturated fats by adding hydrogen atoms (hydrogenation).

Proteins are the most abundant molecules in cells, making up about 50% of the dry mass. Protein molecules range from soluble globules that can pass through cell membranes and set off metabolic reactions (e.g. enzymes and hormones) to the long, insoluble fibres that make up connective tissue and hair. Proteins are made up from amino acids, of which 20 are used by living organisms. Each amino acid has specific properties, depending on its structure, and when they combine together to form a protein, a unique complex molecule is formed. All proteins have unique shapes that allow them to carry out a particular function in the cell. All amino acids are organic compounds that contain both an amino ( $\text{NH}_2$ ) and a carboxyl ( $\text{COOH}$ ) group. Proteins are very important foods, both nutritionally and as functional ingredients, because proteins in the diet serve primarily to build and maintain cells, but their chemical breakdown also provides energy, yielding almost the same as carbohydrates.

In addition to the main groups of carbohydrates, fats and proteins, living organism need countless numbers of minerals and trace elements for them to be able to function adequately. Among these are calcium, iodine, iron, magnesium, manganese, phosphorus, selenium and zinc.

### 1.3.4 Oxidation–reduction potential

The oxidation–reduction (redox or O/R) potential is the tendency of a substance to acquire electrons and thereby convert to its reduced state. O/R potential is measured in millivolts (mV) or Eh ( $1 \text{ Eh} = 1 \text{ mV}$ ) relative to the standard hydrogen electrode (SHE), which is arbitrarily given a potential of 0.00 volts. Different foods have their own intrinsic reduction potential; the more positive the potential, the greater the affinity for electrons and tendency to be reduced. Microorganisms display varying degrees of sensitivity towards the redox potential.

As microorganisms grow, they can affect the Eh of their environment. The Eh of the food is also affected by the characteristic O/R of the food, the resistance to change exhibited by the

food, the oxygen in the atmosphere and the aeration of the foodstuff. Generally, aerobic microorganisms prefer positive Eh for growth (oxidised), while anaerobic microorganisms prefer negative Eh values (reduced).

### 1.3.5 Antimicrobial resistance

Some foods have inherent antimicrobial activity, that is, they contain naturally occurring substances that restrict microbial growth. Some examples include essential oils (e.g. allicin in garlic, eugenol in cloves, and thymol in sage) and enzymes (e.g. lysozyme in eggs). These only have a minor role in thermal processing and will not be considered in detail.

### 1.3.6 Biological structures

The natural covering of some foods (e.g. skins and shells) provides a natural physical barrier to prevent ingress to the moist, nutrient rich, fleshier parts of the plant or animal. Thermal processing usually requires these protective barriers to be removed during preparation, and it is after this point that the foods are at their most vulnerable to microbiological growth and cross contamination.

### 1.3.7 Relative humidity

Relative humidity (RH) is a term used to describe the amount of water vapour that exists in a gaseous mixture of air and water, as given in Equation 1.3:

$$RH = \rho(H_2O)/\rho^*(H_2O) \times 100\% \quad (1.3)$$

where  $RH$  is the relative humidity of the mixture being considered,  $\rho(H_2O)$  is the partial pressure of water vapour in the mixture, Pa, and  $\rho^*(H_2O)$  is the saturated vapour pressure of water at the mixture temperature, Pa.

The RH of the storage environment is important for microbial growth, because it can affect the water activity of the food. Foods and microbial hosts can pick up or lose moisture to the environment as a direct result of the relative humidity, as well as allow growth of microorganisms on the surface of foods if the RH is high enough. Foods with low water activity will pick up moisture from the atmosphere until equilibrium is reached.

The use of RH as a hurdle to microbial growth is considered in greater detail in Chapter 2.

### 1.3.8 Oxygen content/concentration of gases in the environment

Controlling the availability of free oxygen is one means of controlling microbial activity within a food. Although oxygen is essential to carry out metabolic activities that support all forms of life, some microorganisms use free atmospheric oxygen, while others metabolise the oxygen (reduced form) that is bound to other compounds such as carbohydrates.

Microorganisms can be broadly classified into two groups – aerobic and anaerobic. Aerobes grow in the presence of atmospheric oxygen, while anaerobes grow in the absence of atmospheric oxygen. In between these two extremes are the facultative anaerobes, which can adapt and grow in either the absence or presence of atmospheric oxygen and microaerophilic organisms, which grow in the presence of reduced amounts of atmospheric oxygen. Microorganisms have very specific oxygen requirements and can be classified as:

- obligate aerobes (need oxygen);
- obligate anaerobes (need an absence of oxygen);
- facultative anaerobes (grow in the absence or presence of oxygen).

The gaseous composition of the environment will therefore affect the growth rates of specific microorganisms. Modified atmosphere packaging describes the practice of modifying the composition of the internal atmosphere of a food package in order to improve the shelf-life. The modification process lowers the amount of oxygen ( $O_2$ ) in order to slow down the growth of aerobic organisms and the speed of oxidation reactions. The removed oxygen can be replaced with nitrogen ( $N_2$ ), or carbon dioxide ( $CO_2$ ), which can lower the pH and/or inhibit the growth of bacteria.

### 1.3.9 Temperature

Microorganisms grow over a wide temperature range, with the lowest reported being  $-34^\circ\text{C}$  and the highest close to the boiling point of water ( $100^\circ\text{C}$ ). All microorganisms do, however, have an optimum temperature range in which they will grow best.

This preference for temperature forms the basis of dividing microorganisms into groups, for example:

- Psychrophiles have an optimum between 12 and 15°C, but can grow up to 20°C.
- Psychrotrophs have an optimum between 20 and 30°C, but can grow as low as 0°C.
- Mesophiles have an optimum between 30 and 42°C, but can grow between 15 and 47°C.
- Thermophiles grow optimally between 55 and 65°C, but can grow between 40 and 90°C.

Just as moulds are able to grow over a wide range of pH values and moisture conditions, they can also tolerate a wider temperature range than bacteria. Yeasts are not usually found growing in the thermophilic temperature range, but prefer psychrophilic and mesophilic temperatures. Some bacteria produce very heat resistant endospores, and even though most vegetative cells of yeast, mould or bacteria are destroyed at 65°C, the bacterial spores can persist for many minutes at high temperatures (e.g. 121.1°C).

## **1.4 DESCRIPTION OF SOME MICROORGANISMS OF IMPORTANCE TO THERMAL PROCESSING**

All food poisoning microorganisms are of concern in any prepared foods, but for sterilised processed foods, those that can form heat resistant spores are of particular interest as they can potentially survive the thermal process (Stumbo, 1965). Some thermophilic bacteria can form spores that are extremely heat resistant (e.g. spores of *Clostridium thermosaccarolyticum* have been recorded with D-values as high as 195 minutes at 121°C). Fungi are less of a concern to sterilised products as even the most heat resistant fungi cannot survive about 95 to 100°C and subsequently are more of a problem for pasteurised foods or as a result of post processing contamination.

For commercially produced foods, safety is of the utmost importance, but stability of the products is also very important, because food that is spoilt cannot be sold (Goldblith, 1971, 1972). Commercial sterility of thermally processed foods means the condition achieved by the application of heat, which renders the food free from microorganisms capable of reproducing in the food under ambient (i.e. normal non-refrigerated) conditions of storage and distribution as well as any viable microorganisms, including spores, of public health

significance. Below is a list of many of the microorganisms that can affect the commercial sterility of thermally processed foods.

### 1.4.1 Moulds

Vegetative mould filaments (hyphae) are destroyed by relatively mild heat (65°C). Moulds of greatest importance in foods multiply by zygospores, conidia or ascospores that are all more heat resistant than the vegetative organisms. Ascospores in particular can be highly heat resistant (e.g. *Byssoschlamys fulva* produces ascospores that have a D-value at 90°C of between 1 and 12 minutes). Although rarely implicated in food poisoning incidents with thermally processed foods, as mentioned previously, some moulds produce mycotoxins that can cause food poisoning or illness. Some of the moulds found associated with food spoilage are listed below:

- *Byssoschlamys* spp. can cause spoilage in canned fruit as a result of its heat resistant ascospores and the pectinases that they produce. They produce mycotoxins.
- *Rhizopus stolonifer* is readily killed by heating, but can produce heat-stable pectinases that can persist and cause soft rot that makes even canned fruit or vegetables soft and mushy.
- *Aspergillus* has been implicated in the spoilage of a large number of foods including bacon, bread, peanuts, fish, etc. They produce mycotoxins.
- *Fusarium* spp. have extensive mycelium with tinges of brown, red, purple and pink. They cause brown rot on citrus fruit and pineapples, and can grow on cereal crops. They produce mycotoxins.
- *Penicillium* moulds typically spoil fruits, causing blue and blue-green colouration. They produce many different mycotoxins.

### 1.4.2 Yeasts

Yeasts can grow over a wide pH range and also exhibit tolerance to compounds traditionally used in food preservation. For example, some can grow in up to 18% alcohol and others in up to 60% sucrose, 24% NaCl or in  $a_w$  solutions as low as 0.65. Yeasts are not very heat resistant and are generally destroyed at 60 to 65°C, but can cause food spoilage as a result of organisms entering leaking containers post-process.

Some examples of yeasts that can cause food spoilage include the following:

- *Rhodotorula* is a diverse organism that can grow in high sugar concentrations and is implicated in the spoilage of jams, jellies and candies. It can grow well at refrigerator temperatures as well as on the surface of butter.
- *Zygosaccharomyces* spp. can grow in high sugar concentrations and can cause spoilage of jams and jellies. *Z. rouxii* can grow at pH values as low as 1.8 and water activity as low as 0.62.
- *Brettanomyces* spp. produces acetic acid from glucose under aerobic conditions and can cause spoilage in beer, wine and other fermented products.
- *Debaryomyces* spp. can grow in 25% NaCl and at water activities as low as 0.65. It has been found to cause a slimy growth on salted meats, cheeses and in brines. It is also one of the causes of spoilage of yogurt.
- *Saccharomyces bailii* is a spoilage yeast causing spoilage in mayonnaise, tomato sauce, fruit drinks and wine. It is resistant to benzoate and sorbate preservatives.

### 1.4.3 Bacteria

Bacteria are the most important group of food poisoning and food spoilage organisms that must be considered in heat processed foods (Pflug, 2003). Bacteria can be divided into groups depending on the temperature at which they grow, as indicated in the temperature classification earlier in this chapter. Table 1.3 presents some heat resistance data for spores of various bacteria that are important in thermal processing. Note that the terms D- and z-value are described in Chapter 3, which discusses the mathematical basis for thermal process calculations. However, the D-value is a measure of the heat resistance of a microorganism and the z-value provides information on how this heat resistance changes with temperature.

#### 1.4.3.1 Thermophiles

*C. thermosaccharolyticum* is one of the most heat resistant microorganisms that food processes come into contact with. It is a Gram positive, rod-shaped anaerobic bacterium. These bacteria are saccharolytic, and produce large quantities of CO<sub>2</sub> and H<sub>2</sub> (which causes blowing of the cans). They are not tolerant to high levels of acidity but are important in products of moderate acidity. Where these organisms are implicated in spoilage, they are usually introduced to the product with the raw materials, because conditions for their proliferation in the plant and processing equipment seldom exist (the bacteria being anaerobic).

**Table 1.3** Typical heat resistance of spores of some bacteria.

Species	Temperature (°C)	z-value (°C)	Typical D-value (minutes)
<b>Mesophiles</b>			
<i>Bacillus cereus</i>	100		5.5
	121		2.37
<i>B. coagulans</i>	121		3.0
<i>B. licheniformis</i>	100		13.0
<i>B. subtilis</i>	121		0.3–0.7
<i>B. coagulans</i>	100		9.5
	121		1.6–3.4
<i>Clostridium butyricum</i>	85		12–23
	100		0.1–0.5
<i>C. sporogenes</i>	121		0.2–1.5
<i>C. perfringens</i>	100		0.3–17.6
<i>C. botulinum</i> *	121	10.0	0.21
<i>C. botulinum</i> Type A (proteolytic)	121	9.0	0.13
<i>C. botulinum</i> Type B (proteolytic)	121	11.0	0.15
<i>C. botulinum</i> Type B (non-proteolytic)	82	8.3–16.5	1.5–32.3
<i>C. botulinum</i> Type E (non-proteolytic)	77		0.7–1.95
<i>C. botulinum</i> Type F (proteolytic)	121	9.3–12.1	0.14–0.22
<i>C. botulinum</i> Type F (non-proteolytic)	77		1.6–9.5
<i>C. botulinum</i> Type G (proteolytic)	116	20.9–27.3	0.25–0.29
<b>Thermophiles</b>			
<i>Geobacillus</i>	121	7.7	6–16.0
<i>stearothermophilus</i>			
<i>Desulphotomaculum nigrificans</i>	121	9.5	55.0
<i>C. thermosaccharolyticum</i>	121	6.9–11.0	68.0–195.0
<b>General microorganisms</b>			
Vegetative bacteria, yeasts and moulds	65		0.5–1.00

\* Most commonly used for thermal process calculations

*G. stearothermophilus* (used to be *Bacillus stearothermophilus*) is a rod-shaped, Gram-positive bacterium. It is a thermophile and is widely distributed in soil, hot springs, ocean sediment, and is a cause of spoilage in food products by producing various organic acids. No gas is formed and it produces 'flat sour' spoilage in canned foods. It will grow within a temperature range of 30 to 75°C but optimally at



55°C. Spores of *G. stearotherophilus* may enter a cannery in soil, on raw foods, and in ingredients such as spices, sugar, soya meal, flour and starches. Populations may increase at any point where proper environmental conditions exist (i.e. food handling equipment in a canning line that is operated within the thermophilic growth range, such as blanchers). Their presence in some processed containers of commercially sterile low-acid foods may be considered normal and not of particular concern because, although *G. stearotherophilus* can grow at temperatures as low as 30 to 45°C, the spores will not develop if the product is stored at temperatures below 43°C. Therefore proper cooling after thermal processing and the avoidance of high temperatures during warehouse storage and distribution are essential in controlling its outgrowth.

*D. nigrificans* is a strict anaerobic thermophile. These bacteria can cause the so-called 'sulphide stinker' spoilage. They produce hydrogen sulphide ( $H_2S$ ) in the product, resulting in a bad odour (resembling the odour of rotten eggs). The  $H_2S$  dissolves in the contents of the containers, and the containers often remain 'flat'. In cans, the  $H_2S$  interacts with the iron in the containers, resulting in the contents discolouring to black. This bacterium used to be classified as a Clostridia, and is still referred to as *Clostridium nigrificans* in some textbooks.

*Alicyclobacillus acidoterrestris* is a thermoacidophilic, non-pathogenic, spore-forming bacterium. *A. acidoterrestris* spores are resistant to low pH pasteurisation and they can germinate and grow causing spoilage, characterised by a medicinal or disinfectant smell attributed to a chemical guaiacol (o-dihydroxybenzene) that the organism produces. It is an unusual organism in that it is almost the only thermophilic organism that can tolerate high acid conditions. It is found in soils of fruit orchards and enters processing environments as a contaminant of raw materials.

#### 1.4.3.2 Mesophiles – spore-forming bacteria

Food poisoning incidents that result in fatalities are incredibly rare. However, one bacterium that can cause death is *C. botulinum*. The botulinum toxin is one of the most potent neurotoxins known, to the extent that it is used in biological warfare. Food contaminated with only a few nano grams ( $10^{-9}$  g) can be toxic. For this reason, while fairly uncommon, the risk is taken very seriously by all producers of products packed in an anaerobic environment and stored for an extended period of time (e.g. canned and vacuum packed food). All low acid food processes are designed with organisms such *C. botulinum* in mind (Rees and Bettison, 1991).

*C. botulinum* are Gram-positive, obligate anaerobe, spore-forming bacteria. They are commonly found in soils throughout the world, in any region. Since they are found in the soil, they contaminate vegetables cultivated in or on the soil and will colonise the gastro-intestinal tract of fish, birds and mammals.

*C. botulinum* are classified as a single species of bacteria but includes at least three genetically distinguishable groups of organisms that have been recognised to be toxic for humans (*C. botulinum*, *C. baratii* and *C. butyricum*). These organisms share the ability to produce the neurotoxins. The toxin types are classified as A, B, C, D, E, F and G. Human botulism has been described with the strains of *C. botulinum* that produce toxin type A, B and E.

*C. botulinum* bacteria produce spores that are heat resistant and cannot be killed simply by boiling. Canned food sterilisation processes are specifically designed so as to eliminate the possibility of any spores surviving. The toxin is, however, more heat sensitive and heating at 80°C for 30 minutes or 100°C for 10 minutes will destroy the active toxin.

Factors that limit the growth of *C. botulinum* include the following:

- *Low pH*: *C. botulinum* will not produce toxin in acid or acidified foods (i.e. below pH 4.6).
- *Low water activity*: A minimum  $a_w$  of 0.94 is needed to support bacterial growth and toxin production. This water activity corresponds to a 10% salt (NaCl) solution, which is why salting is sometimes used as a method of preservation.
- *Temperature*: Most strains grow optimally at 40°C, but some of the psychophilic strains can grow at temperatures as low as 3°C.
- *Food preservatives*: Many preservatives (nitrite, sorbic acid, phenolic antioxidants, polyphosphates, etc.) inhibit *C. botulinum* growth.
- *Competing microorganisms*.

There are a number of other mesophilic bacteria of importance in thermal processing. The main ones are described below, and will feature in other places in this book (*FDA Bad Bug Book*).

*B. coagulans* are thermotolerant and acid-tolerant bacteria that have been isolated from canned tomato products, where they cause a reduction in the pH of spoiled products by acid production without CO<sub>2</sub> formation. The ends of the spoiled containers therefore remain flat, and the bacteria can also be termed 'flat-sour'

bacteria. Optimal growth is between 37 and 45°C and at pH levels between 5.0 and 7.0. *B. coagulans* is not as heat-resistant as *G. stearothermophilus* but can grow at lower pH values (e.g. down to pH 4.2).

*C. butyricum* is a Gram positive, spore-forming, anaerobe. These bacteria spoil moderately acid food such as canned peaches and other fruit with pH values above 4.0, as well as canned vegetables (e.g. peas, potatoes) and other products of low acidity. Butyric acid and gas are produced during their metabolism.

*C. perfringens* are Gram-positive, spore-forming, anaerobic rod-shaped bacteria. They are widely distributed in Nature and also found associated with the intestines of animals and humans. The spores are not particularly heat resistant (when compared with spores of *C. botulinum*) and food poisoning from this organism is usually associated with cooked foods that have been inadequately cooled and held for several hours before consumption. This organism produces a toxin that causes intense abdominal cramps and diarrhoea.

*B. cereus* are Gram-positive, facultative aerobic, spore-forming rod-shaped bacteria. The spores of this organism are also not particularly heat resistant. Presence of this organism in large numbers can result in two types of food poisoning illnesses: A protein toxin that causes diarrhoeal symptoms, similar to that caused by *C. perfringens*, and a heat stable peptide that causes vomiting symptoms, similar to that caused by *Staphylococcus aureus*. The diarrhoeal type of illness has been diagnosed after consumption of a variety of foods (e.g. milk, meat, fish and vegetables), while the vomiting type is associated with consumption of rice products and other starchy foods such as potatoes and pasta. Puddings, soups, casseroles, pastries and salads have all been implicated with food poisoning by this bacterium.

#### 1.4.3.3 Mesophiles – non-spore forming pathogenic and spoilage bacteria

*Salmonella* spp. are Gram-negative, rod shaped, motile bacteria that do not form spores. They are widespread in occurrence, being found for example in fresh and salt water, soil and animal faeces. Various foods have been found to be associated with Salmonellosis, the illness caused by the *Salmonella* spp., including raw meat, poultry and seafood, raw eggs and foods made from raw eggs, dried gelatine, cocoa, chocolate, peanut butter, yeast and coconut. Salmonellosis is caused by infection with the organism and extremely low doses (levels as low as 15 cells) can cause the disease.

*Staphylococcus aureus* are Gram-positive, small round bacteria (cocci) that can produce a heat stable toxin. Less than 1 µg of toxin can cause illness. *S. aureus* are found everywhere, but the most common source of contamination of food is via humans, i.e. food handlers. *Staphylococci* are found in the nasal passages, throats, on the skin and hair of more than half of healthy people. Intoxication is caused by contaminated food being held either not hot enough (i.e. <60°C) or not cold enough (i.e. >8°C), which allows the organism to grow and produce its toxin. The symptoms (nausea, vomiting, cramping) of Staphylococcal food poisoning are very fast (a few hours) and usually acute.

*Escherichia coli* are Gram-negative bacteria that are found in the intestines of all mammals, including humans. *E. coli* produce toxins that can cause four different classes of illnesses that are of concern to the food industry. The first class is enterovirulent (EEC) that causes gastroenteritis; this class includes *E. coli* 0157:H7 (EHEC), which is enterohaemorrhagic. The second type is referred to as enterotoxigenic (ETEC), the third is enteropathogenic (EPEC) and the fourth is enteroinvasive (EIEC). Outbreaks of food poisoning due to *E. coli* are usually associated with faecal contamination of water by food handlers or due to unprocessed or under-processed (and under-cooked) foods. The recent interest in organic food production systems has enabled *E. coli* to grow and contaminate fruit and vegetable raw materials, resulting in outbreaks in pasteurised apple juice.

Lactic acid bacteria are a large diverse group comprising of bacteria from *Lactobacillus*, *Lactococcus*, *Leuconostoc*, *Pediococcus*, *Streptococcus*, etc. These bacteria are commonly involved with fermentation reactions that are desirable, but can also cause spoilage by acid and gas formation in some products. Post-process recontamination is the most likely cause, if a spoilage incident is attributed to lactic acid bacteria. This is because these bacteria are not at all heat resistant.

#### 1.4.3.4 Psychrophiles

There are very few psychrophiles of concern in thermal processing; however, one of the few that can cause problems with cook-chill foods is *Pseudomonas* spp. This is a large group of Gram-negative rod-shaped bacteria that are responsible for spoilage of many refrigerated proteinaceous products (e.g. meat, fish, eggs). Some strains produce blue-green pigments. They are implicated in many food spoilage conditions (e.g. green rot, black rot, pink rot and red rot). They have very varied nutritional requirements and can even cause spoilage of bottled water.

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## 2 Hurdles to Microbial Growth

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Food preservation is the process of treating food to stop or slow down spoilage (loss of quality or nutritional value) caused or accelerated by microorganisms and/or intrinsic enzymes. A number of hurdles to microbial growth are described, including water activity, pH, storage temperature, and preservatives such as salt and sugar. These can be used alone or in combination.

Heat treatment is an extremely effective means of food preservation, but a full sterilisation of foods is not always appropriate, as the nutritional value, texture and/or colour of the food could be unacceptably changed. In these instances a mild heat treatment, together with at least one other method of food preservation is used. When a combination of two or more food preservation factors is used, generally each factor can be used at a slightly lower level. Using more than one food preservation factor or hurdle is termed 'hurdle technology'. Hurdle technology uses the intelligent combination of different preservation factors or techniques to achieve multi-target, mild but reliable preservation effects (Leistner, 2000). It is usually more effective than single targeting and allows hurdles of lower intensity, with the benefits of improved product quality (Lee, 2004).

According to Leistner (1999), the number of already applied and potential hurdles for the preservation of foods amounts to over 100. As our understanding of the mode of action of food preservation improves, factors such as microbial metabolic exhaustion, stress reactions and homeostasis are taken into account when considering food preservation. The traditional methods of heating, chilling, drying, curing, acidification, oxygen removal, fermenting and adding chemical preservatives are frequently used (Table 2.1), but newer methods such as pulsed technologies and 'natural' preservatives are also being employed. To use all of these food

**Table 2.1** Selected food preservation techniques and their effect on spoilage microorganisms.

Method	Effect on microbial growth or survival
Refrigeration	Low temperature to retard growth
Freezing	Low temperature and reduction of water activity to prevent microbial growth, slowing of oxidation reactions
Drying	Reduction in water activity sufficient to delay or prevent microbial growth
Vacuum and oxygen free modified atmosphere packaging	Low oxygen tension inhibits strict aerobes and delays growth of facultative anaerobes
Modified atmosphere packaging (enriched CO <sub>2</sub> )	Specific inhibition of some microorganisms
Addition of weak acids; e.g. sodium lactate	Reduction of the intracellular pH of microorganisms
Sugar preservation	High osmotic pressure causes inhibition of growth or death
Ethanol preservation	Ethanol is toxic to microorganisms and causes inhibition of growth or death
Addition of preservatives (e.g. nitrite or sulphite)	Inhibition of specific groups of microorganisms by interfering with cell membrane functioning
Pasteurisation	Delivery of heat sufficient to inactivate target microorganisms to the desired extent
Irradiation	Delivery of ionising radiation to disrupt cellular RNA
Pulsed electric field processing	Short bursts of electricity for microbial inactivation

preservation methods, a good understanding of the biochemistry of the mode of action is required.

The most commonly used hurdles that are combined with thermal processing are discussed below. Some discussion of these has already taken place in Chapter 1 but the relevance of these factors to mild pasteurisation is stressed here:

- (i) control of the load of microorganisms;
- (ii) use of restrictive pH;
- (iii) use of anaerobic conditions;
- (iv) use of low temperatures;
- (v) drying/low water activity;
- (vi) chemical preservation;
- (vii) irradiation.

## 2.1 CONTROL OF THE MICROORGANISM LOADING

Shells, skins, membranes and fat are the natural defences that prevent microbial contamination of meat, fish, fruit and vegetables prior to harvesting. Once these barriers are removed, there are a number of methods that can be used to physically remove microorganisms from foods, which includes:

- Washing of raw foods, which is an important part of most ingredient preparation, but may result in increasing the microbial load if the water used for washing is not clean. Washing can also increase the food's moisture content and thus increase the spoilage potential.
- Trimming includes the removal of spoiled portions. It is an important step in ensuring that the load of an ingredient batch is kept as low as possible.
- Filtration is limited to clear liquids, but is used successfully with some fruit juices, beer, wine, soft drinks and water.
- Centrifugation or sedimentation is used in some milk and juice production.

Reducing the initial microbial load is critical because it determines the extent of heat process time and temperature that must be applied to achieve the condition of commercial sterilisation. Although it is important to ensure that a food process starts with a low load, it is also important to understand why each step of a process is being done, because this helps to understand the importance of that step. This is where the HACCP plan is used to ensure levels of microbial contamination are low. However, it is important to note that even if microorganisms are removed from food, various pre-formed enzymes and/or toxins might remain and present problems.

## 2.2 USE OF RESTRICTIVE pH LEVELS

Preventing the growth of microorganisms by lowering the pH is a very old food preservation technique (Chapters 4 and 5). Pickling refers to preserving foods using inorganic acids (and often salt), originally due to fermentation, but more recently also by addition of acids to the food product. Commercially pickled products are almost always now given a heat treatment of sorts. Figure 2.1 shows examples of materials of varying pH from battery acid at around pH 0 through to strong alkalis at pH 14.



pH 0	Battery Acid (30%) H <sub>2</sub> SO <sub>4</sub>
pH 1	Gastric Acid (1.1)
pH 2	Cola (2.5)
pH 3	Apricots (3.2)
pH 4	Tomatoes (3.8–4.4)
pH 5	Rain (5.5)
pH 6	Egg Yolk (5.7)
pH 7	Human Blood (7.2)
pH 8	Egg Whites (8.5)
pH 9	Baking Soda (8.5)
pH 10	Milk of Magnesia (10.6)
pH 11	Household Ammonia (11.2)
pH 12	Household Bleach (NaClO) (12.6)
pH 13	Household Lye (NaOH) (13.5)
pH 14	Concentrated Sodium Hydroxide (NaOH)

**Fig. 2.1** Materials of varying pH from battery acid at pH 0 through to strong alkalis at pH 14. For a colour version of this figure, please see the colour plate section.

Most microorganisms grow best at neutral pH (6.5–7.5) and only a few are able to grow at pH < 4.0. Bacteria are more fastidious about their pH requirements than are yeasts and moulds. The fact that pH can limit microbial growth is a basic principle of food preservation and has been used for thousands of years. Fermentation and pickling extend the shelf-life of food products by lowering the pH. The fact that no known spore-forming pathogenic bacteria can grow at pH < 4.6 is the basis for the food sterilisation principle for low acid and acid foods.

Foods can be classified according to the pH/acidity of the product, with the following classification proving useful when assessing spoilage incidents:

- Low acid foods have pH values exceeding pH 4.5.
- Medium acid foods range in pH from 4.2 to 4.5.
- Acid foods have pH between 3.8 and 4.2.
- High acid foods have pH values below 3.8.

Under normal conditions of storage, bacterial spores that survive commercially adequate processing are incapable of development in acid foods, and this fact has led to the adoption of the term ‘commercial sterility’. This indicates that the microbiological condition is not necessarily completely sterile, but is a safe, marketable food. *Commercially sterile food may be defined as food, which has been so processed, that, under ambient storage conditions, will neither spoil nor endanger the health of the consumer.*

Acid foods need to be heat or otherwise processed to destroy non heat-resistant yeast and bacterial vegetative bacterial cells and mould spores, which are generally not inhibited by low pH alone (Chapter 4).

All microorganisms have a pH range in which they are most comfortable. This is usually around neutral pH, but some microorganisms have a larger range that they can tolerate. Adverse pH affects the respiration of microorganisms; two examples of how they are affected are the functioning of their enzymes and the transport of its nutrients into the cell.

The intracellular pH of a microorganism is virtually constant and so, if a microorganism is placed in an environment that is too acid or too alkaline, it will have to expend a lot of energy to maintain its own internal pH balance. If the pH is too extreme, it can result in the death of the microorganism. Bacterial cells have an overall negative charge and so non-ionised compounds can enter the cell, while ionised ones cannot. At neutral and alkaline pH, organic acids do not enter, but at acidic pH these organic acids are non-ionised and can therefore enter the negatively charged cell. This is why the effect of an organic acid is enhanced at low pH, even though they are weak acids.

## **2.3 ANAEROBIC ENVIRONMENT OR MODIFIED ATMOSPHERE ENVIRONMENT**

Modified atmosphere describes the practice of modifying the composition of the internal atmosphere of a package in order to improve the shelf-life. The process often aims to lower the amount of oxygen ( $O_2$ ), moving it from 21 to 0% in order to slow down the growth of aerobic organisms and the rate of oxidation. The removed oxygen can be replaced with nitrogen ( $N_2$ ), which is functionally inert, or carbon dioxide ( $CO_2$ ), which can lower the pH or inhibit the growth of bacteria. The lack of oxygen will inhibit aerobic microorganisms only and can provide an atmosphere that is preferred by anaerobic organisms. However, the anaerobes generally have naturally slower generation times than the aerobes and so their numbers will increase slowly if the modified atmosphere is combined with chilled storage. A disadvantage is that anaerobic conditions will give anaerobic spoilage organisms a selective advantage, which might not be advisable for certain foods.

For thermally processed foods, the use of modified atmospheres tends to be for foods that oxidise during the lengthy storage at

ambient temperature. It is not usual for modified atmospheres to enhance the microbiological shelf-life because the heat process is designed to achieve this aim.

**2.4    LOW TEMPERATURES**

Low temperatures are used to retard chemical reactions such as the actions of food enzymes, and to slow down or stop the growth and activity of microorganisms in food. The lower the temperature, the slower will be the chemical reaction, the enzyme actions and the microbial growth. A temperature below 0°C will prevent the growth of microorganisms, although in practice 3°C is often considered to be a temperature sufficiently low to control (stop) microorganism growth. Low temperatures are inhibitory to growth, rather than lethal to the microorganisms. Table 2.2 presents minimum growth temperature for selected microorganisms.

Chilling is often used together with a mild heat treatment (e.g. 2 minutes at 70°C is a guideline to eliminate pathogens such as *Salmonella*, *Escherichia coli* and *Listeria*). A further hurdle of ‘lowering the load’ of microorganisms in the food is usually also used, as described in the section above, by working in a clean environment and applying the appropriate packaging to protect the food or ingredients.

Freezing stops multiplication of microbial cells. The water activity ( $a_w$ ) of the product will drop due to crystallisation of the available water. Although there might be an initial decrease in cell numbers due to ice crystal formation, which may rupture the cells, many microorganisms may survive freezing and continue proliferation and growth once the product is thawed. The spoilage

**Table 2.2** Minimum growth temperatures for some pathogenic bacteria (taken from Campden BRI, 1996).

Organism	Minimum growth temperature (°C)
<i>Bacillus cereus</i>	4.0
<i>Clostridium botulinum</i> (psychotropic)	3.3
<i>E. coli</i> 0157	7.0
<i>Listeria monocytogenes</i>	−0.4
<i>Salmonella</i> sp.	4.0
<i>Staphylococcus aureus</i>	6.7
<i>Vibrio parahaemolyticus</i>	5.0
<i>Yersinia enterocolitica</i>	−1.0

potential of the product will actually increase on thawing, as the texture changes and drip water forms.

Freezing does not destroy microbial toxins and viruses. Food that shows signs of microbial spoilage is not necessarily poisonous, and food that contains microbial toxins does not always appear spoilt. When low temperature is used for food preservation, either solely or in conjunction with mild heat processing, it is important to take cognisance of the 'use by' date.

## 2.5 DEHYDRATION OR LOW WATER ACTIVITY

Microorganisms cannot grow in a water-free environment, because enzyme activity is absent and most chemical reactions are greatly slowed down. This is the principle behind dehydration or low water activity foods.

Fresh vegetables, fruit, meat and fish have naturally high moisture content, which averages about 80%. Drying reduces the amount of moisture, thereby limiting the numbers and types of microorganisms that can grow, and reduces the rate at which they can do so. There are different methods of drying that can reduce the moisture content slightly or virtually completely, depending on the desired effect, for example:

- sun drying;
- drying by mechanical means; e.g. hot air drying, spray drying, roller drying;
- freeze drying; sublimation of water from a frozen food by means of a vacuum.

Some foods (e.g. jams, marmalades) have relatively high moisture content, but the moisture is chemically bound (to sugar in the case of jam) and not available to the microorganisms. A measure of the availability of water is called *water activity* and is defined by the ratio of the water vapour pressure in the food substrate to the vapour pressure of pure water at the same temperature, and is denoted by  $a_w$ . Pure water has a water activity of 1.0, while most fresh foods have a water activity of about 0.99.

In general, bacteria require a higher  $a_w$  than yeasts and moulds. Most spoilage bacteria cannot grow at  $a_w < 0.91$ , with *C. botulinum* having a minimum growth level of 0.94. However, *S. aureus* has been found to grow at  $a_w$  as low as 0.84. The lowest reported  $a_w$  value for a bacterial growth was 0.75. Most spoilage moulds cannot grow at  $a_w < 0.80$ , with the lowest reported  $a_w$  for any mould growth at 0.65 and for yeasts at 0.61.

High salt and high sugar mixtures preserve food because they either kill the microorganisms directly due to the difference in osmotic pressure, or they bind the free water and lower the water activity, so that there is no water left for the microorganisms to use for growth. They effectively dry the product out. With salt or sugar, we can theoretically preserve food for decades without it being consumed by bacteria. The value of this method to reliably preserve food cannot be understated. Before refrigeration (~100 years ago) sugar preserves were one of the only ways to keep fruit throughout the winters. Similarly salt was, and still is, used to preserve fish, meat and vegetables for many months.

In thermal processing it is common to use low water activity as a hurdle technology that is applied in combination with a thermal process. Modern jams contain sufficient acidity and sugar to avoid the need for a full botulinum process; however, a mild pasteurisation process is required to provide a shelf stable product. Other examples of low water activity in combination with a mild process include pesto, sun dried tomatoes and fermented meats such as salami.

## 2.6 CHEMICAL PRESERVATION

Some chemicals have specific antimicrobial activity and can be used to control the growth of microorganisms in food. Naturally occurring antimicrobial chemicals are present in herbs and spices and have been used traditionally for thousands of years. More recently, as our understanding of food science has improved, a range of specific active chemicals is used. The use of chemical preservatives is strictly controlled by legislation in the appropriate country, as is the quantity that may be used.

Chemical preservatives may inhibit microorganisms by interfering with the cell membranes (influencing cell permeability), enzyme activity and/or genetic mechanisms. Most chemical preservatives have the highest activity at low pH.

Properties required of an ideal chemical preservative include:

- wide range of antimicrobial activity;
- non-toxic;
- economical;
- must not affect the sensory qualities of a product;
- kill rather than inhibit.

Examples of chemical preservatives are many and include the following:

- benzoic acid, propionic acid, sorbic acid and their salts;
- sulphur dioxide, methyl and ethyl parabens;
- nitrates and nitrites;
- antioxidants, e.g. BHA, BHT, TBHQ;
- antibiotics, e.g. Pimaricin (Delvocid), Nisin (Nisaplin); however, no antibiotics of medical significance may be used in foods.

The mode of action of preservatives can be very specific and varies from compound to compound, and so the desired effect must be carefully considered when using preservatives.

### 2.6.1 Organic acids

Acetic acid (vinegar) is known to cause disruption of the cell membrane. It also causes denaturation of proteins inside the cell. Acetic acid is highly effective and widely used as an acidulant and preservative. Only some bacteria (*Acetobacter* spp. and some lactic acid bacteria) and some yeast and mould are resistant to acetic acid. The growth of most food poisoning bacteria is inhibited by 0.1% acetic acid. Many pickles, mustards and dressings use acetic acid in their formulation, with a pasteurisation treatment of 2 minutes at 70°C for products below pH 3.7.

Sorbic acid causes membrane damage of many microorganisms and disrupts enzyme activity inside the cells. It is widely used to inhibit the growth of yeast, mould and some aerobic Gram positive bacteria. However, it is relatively ineffective against lactic acid bacteria. Sorbic acid is more effectual at low pH and has virtually no effect above pH 6. It is widely used in pH controlled drinks, such as fruit squashes, with a mild process of 2 minutes at 70°C.

Benzoic acid has a similar mode of action to sorbic acid, but is used mainly to control the growth of yeast and mould (at levels of 0.05–0.10%). Often both benzoic and sorbic acids are used together so their effect is increased.

Propionic acid is similar in action to the other organic acids, but is used primarily to inhibit mould growth (0.05–0.10%). It is also effective against many bacteria. It is most commonly used in baking to prevent ropiness caused by *Bacillus subtilis* survival through the baking process.

### 2.6.2 Sulphites and nitrites

Sulphites in the form of sulphur dioxide, sulphite, bisulphites or metabisulphites are used extensively to control the growth of undesirable microorganisms in fruit, fruit juice, wine, meat, fish

and pickles. At low pH (<4.0), it inhibits yeast and mould and at higher pH values it inhibits spore-forming bacteria. As the pH gets lower, more of the compound is in the sulphur dioxide form (from bisulphite form). The sulphur dioxide is believed to pass through the cell membrane by diffusion and then disrupt normal cell metabolism.

Nitrites enter the cell via the cell membrane and disrupt normal metabolic pathways and cellular respiration via formation of a variety of complex compounds. Nitrates are mainly used to inhibit bacterial growth. The effectiveness is related to pH, with lower pH being more effective. Nitrites are used widely with meat products so that a lower process can be applied than the full botulinum  $F_0 3$ , usually of the order of  $F_0 1$ .

### 2.6.3 Antibiotics

Nisin is a peptide antibiotic produced by some strains of *Lactococcus lactis*. Its inhibitory effect is restricted to Gram positive bacteria where it causes death of the target organism by cell lysis. Nisin can be used to prevent the spoilage (by *Clostridium* and *Bacillus* spp.) of cheese, milk products, some canned products, cured meats and alcoholic beverages.

### 2.6.4 Antioxidants

Phenolic antioxidants are mainly used to prevent chemical oxidation of foods, but they do have some microbial effect, especially inhibiting bacterial growth (at levels of 100–400 ppm). They have also been shown to reduce toxin production in some bacteria. High protein concentrations reduce the effectiveness of these antioxidants, as does low temperature.

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## 3 Low Acid Canned Foods

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This chapter provides a history of the development of processes for the low acid canned food sector and of the evolution of the minimum botulinum cook or  $F_03$  process. Low acid foods are a group of foods that do not contain any preservation hurdles to microorganism growth and rely on:

- (i) the heat process to control microorganism numbers in the food; and
- (ii) an hermetically sealed package to prevent recontamination.

This means that if the heat process is delivered incorrectly, with the result that containers of food receive sub-lethal processes, there are no hurdles to the growth of any surviving microorganisms in the food. It is therefore likely that some of the surviving microorganisms will germinate from their spores and grow in the food. This will result in either a food safety or food spoilage incident, depending on which group of microorganisms dominates.

Of equal importance to the heat process is the need for the package to prevent recontamination of the food during its long ambient storage. Low acid foods typically have shelf-lives of 18 months or even longer. The declared shelf-life will depend on the eating quality of the food at the end of the shelf-life. Growth of toxin producing microorganisms will not be an issue and so it is chemical degradation of the food over time that gives rise to a limited shelf-life. Much of the food degradation is caused by oxygen in the headspace and trapped within the product, and for this reason most canned foods are closed under vacuum.

The term 'low acid canned food' suggests the acid concentration in the food is at a low level so that it is not a hurdle to the growth of microorganisms. However, the low acid category could



also include foods in which other preservation hurdles are present, for example low water activity (e.g. added sugar or salt) or added preservatives. Both of these hurdles are used in thermal processing to enable a lower severity of process to be delivered in low acid foods. For example, the US FDA regulations state that commercial sterility can be achieved by control of  $a_w$  and heat (FDA: Title 21 Code of Federal Regulations (CFR) Part 113 – Thermally Processed low-acid foods packaged in hermetically sealed containers). The heat is necessary at  $a_w$ 's > 0.85 to destroy vegetative pathogens and spoilage organisms. Chapter 6 describes hurdle technologies in more detail. Despite this apparent confusion, low acid foods are generally known as those in which there are no hurdles to microbial growth.

### **3.1 HISTORY OF THE CANNING INDUSTRY**

The application of high temperatures is one of the most commonly used methods to kill or control the numbers of microorganisms present within foods and on packaging surfaces. Evidence for its importance in today's food industry can be seen in the percentage of shelf space taken up in any retailer by foods preserved by heat. Along with low temperature storage (e.g. refrigeration and freezing) and dried foods, thermal processing remains of key importance to the worldwide food industry. There have been many attempts to introduce foods preserved by new technologies (e.g. ultra high pressure, pulsed electric fields) into retail food markets, but their significance is still relatively minor in comparison with thermal processing.

Thermal processing is a general term that describes all forms of heat treatments in which microorganism numbers are controlled by heat. This includes heat processed container types such as metal cans, plastic trays, pouches, glass jars and even cartons. It also includes continuous thermal processes that take place outside of the package and are usually linked with aseptic or hot filling. Continuous processes are discussed in Chapter 7, which looks at different processing methods. Canning was an early terminology and nowadays the terms 'canning' and 'thermal processing' are often used for the same purpose.

Canning has a long and distinguished history. The canning process dates back to the late eighteenth century in France when Emperor Napoleon Bonaparte, who was concerned about keeping his armies fed, offered a cash prize to whoever could develop a reliable method of food preservation. Nicolas Appert took it upon

himself to discover this method. He found out that the application of heat to food in sealed glass bottles preserved the food from the deterioration experienced with all foods when left in the open. Despite not understanding why the heat process prevented the food from going bad, Appert had founded one of the most important methods of food preservation. In about 1806, Appert's principles were successfully trialled by the French Navy on a wide range of foods including meat, vegetables, fruit and even milk. However, it was not until 50 years later that Louis Pasteur provided the explanation for the effectiveness of canning when he demonstrated that growth of microorganisms was the cause of food spoilage.

An Englishman, Peter Durand, took the process one step further towards the modern-day metal can by developing a method of sealing food into unbreakable tin containers. This was later perfected (improved upon) by Bryan Dorkin and John Hall, when they set up the first commercial canning factory in England in 1813. Tin containers had the advantage over glass bottles of being lighter, possessed a better seal and were less prone to damage during transportation and storage. The original food can was made of iron and was coated with a fine layer of tin to stop it from rusting. There is little difference in the external appearance of the original tin cans to the stainless steel cans of today. It has been argued that metal cans have not needed to evolve too much since the 1800s because the original design was so good; the metal can was one of the few examples of a design that was almost perfect from conception. This is a gross simplification of a packaging technology that has evolved from welded seams, thick metal plate and irregular tin coating. Today's metal cans contain a compound within a double pressed seam, substantially thinner steel plate and numerous different types of coatings and lacquers. Metal cans also come in many different shapes and sizes.

The next progression in canning technology was to improve the efficiency of the thermal process. It was discovered that if the food was heated in a steam atmosphere at high temperatures and under pressure, the required heating and cooling times became significantly shorter. The first pressure retort was built in 1851, which allowed steam temperatures greater than 100°C to be used. This provided the benefit of reduced thermal process times that in turn improved the flavour, texture and nutritional value of the food. Steam retorts are still used for processing cans; however, there are now other options available for supplying heat to the container surfaces.

Canned food production was first automated as long ago as 1897 in a factory that produced around 6 cans an hour. This compares with today's production lines that produce in excess of 1500 cans

a minute. After the 1920s, canned food lost its military image and became fully accepted as part of the national diet. In the UK, the Campden Experimental Factory was opened in 1919 as part of the University of Bristol. Its remit was to understand the canning process in greater depth so that canned foods could be manufactured to higher quality and with a greater assurance of food safety. Thermal processing is still a key part of (the now) Campden BRI, with activities within the departments of Food Manufacturing Technologies, Microbiology, Food Hygiene and Chemistry.

Food canning is now a long established and well-understood technique, which has served consumers well for nearly 200 years. It is used to produce a wide variety of shelf stable products that can be stored at ambient temperatures for many months. The basic principles of canning have not changed dramatically since Nicholas Appert and Peter Durand developed the process and packaging, respectively. In simple terms, heat is applied to foods packed into sealed or airtight containers, at levels sufficient to destroy the relevant microorganisms. The amount of time needed for processing is different for each food type, in that it depends on the presence of antimicrobial hurdles (e.g. water activity, acidity, preservatives) and the ability to transfer heat to the food thermal centre. Subsequent chapters describe the impact of various hurdles to microbial growth and the levels of heat treatment required to achieve a commercially sterile food.

The canning process was originally developed to preserve food safely and for long periods of time. Food safety is often taken for granted with thermally processed foods; however, this understates the efforts made by food companies to ensure their products are safe for consumers to eat. Safety of thermally processed foods is closely monitored using a system called Hazard Analysis and Critical Control Point, or HACCP (Bauman, 1974). HACCP is a system that identifies areas of potential contamination within the food process and builds checkpoints, or CCPs, to ensure that the product safety is maintained at all times. Validation of a thermal process and the determination of CCP levels is a challenging exercise that requires a variety of accurate tools. Chapter 9 will mention the role for HACCP in the discussion on process validation.

## **3.2 PRODUCTION OF A THERMALLY PROCESSED FOOD**

Without simplifying too much, the manufacture of a thermally processed food can be broken down into two basic operations:

- (i) The food is heated to reduce the numbers of surviving microorganisms to an acceptably small statistical probability. This includes both pathogenic and spoilage organisms that are capable of growth under the intended storage conditions (DoH, 1994); and
- (ii) The food is sealed within an hermetic package to prevent contamination of the food.

Preservation methods such as traditional canning achieve this by sealing the food in its package before the application of heat to the packaged food product. On the other hand, continuous processing operations heat the food within a heat exchange system prior to dispensing it into the package. Both methods reduce the numbers of microorganisms in the food to commercially accepted levels and the packages prevent recontamination over the shelf-life. Choice of an in-pack or in-line heat process depends on many factors. Primarily the choice is to apply the most suitable heat process to a food product so that its quality is maximised. It is also dependent on the type of packaging and whether an in-pack process is suitable for that packaging. For example, most fruit juices are pasteurised in heat exchangers and filled into cartons or plastic bottles. Neither of these packaging formats is easy to process in the finished package and so a continuous process is the obvious option.

The heat process must target the correct type of microorganism in order that the product has the correct shelf-life. This is because there are millions of types of microorganisms that can grow within food products and the selection of which ones to target is critical. Fortunately only a few can cause damage to our health. Of primary concern from a public health perspective are those that produce toxins such as *Clostridium botulinum*, *Listeria monocytogenes*, *Salmonella*, *Escherichia coli* O175, *Staphylococcus aureus*, *Bacillus cereus* and *Campylobacter*. Food poisoning organisms such as *Listeria*, *Salmonella*, *E. coli* O175 and *Campylobacter* are not very resistant to heat and therefore are not considered when designing processes for low acid foods. These organisms are relevant to certain groups of pasteurised foods in which the levels of heat applied are substantially less than for a full sterilisation process. Chapter 6 considers the types of products, processes and shelf-life requirements that make these organisms the targets for the thermal process.

The requirements of a full sterilisation process for low acid foods are discussed in the next section.

### 3.3 F<sub>0</sub>3 STERILISATION PROCESSES

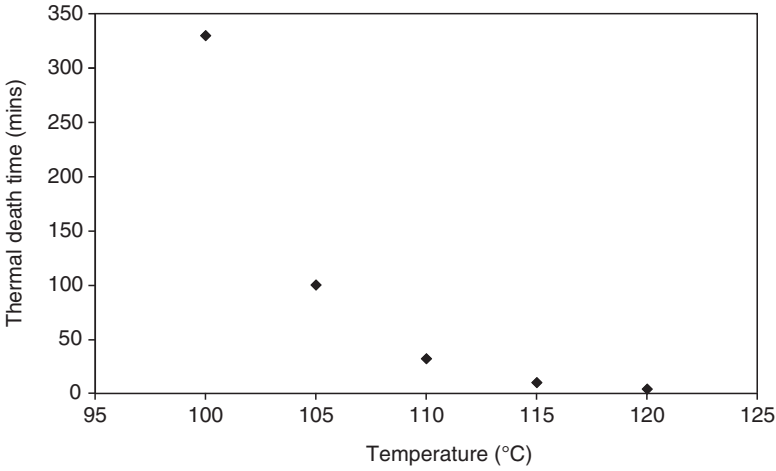
A full thermal sterilisation process is required if no preservation hurdle to microbial growth exists in the food product. For low acid foods, the most heat-resistant pathogen that might survive the thermal process is *C. botulinum* (Esty and Meyer, 1922). This bacterium can form heat-resistant spores under adverse conditions, which will germinate in the absence of oxygen and produce a highly potent toxin that causes a lethal condition known as botulism. This can cause death within seven days and has been implicated in several notorious incidents. The most recent incident in the UK was in 1989, when *C. botulinum* spores survived in canned hazelnut puree, which was used as flavouring for yoghurt. A reformulation of the hazelnut puree to a recipe with lower sugar, but without an increased process, resulted in several blown cans and some containing botulinum toxin.

UK practice is for a commercial sterilisation process to reduce the probability of a single *C. botulinum* spore surviving in a pack of low-acid product to one in a UK billion (i.e. 1 in 10<sup>12</sup>). This is called a 'botulinum cook', and the required heat process to achieve this condition is at least 3 minutes equivalent at 121.1°C, referred to as F<sub>0</sub>3 (DoH, 1994). These terms will be used frequently in this book.

*C. botulinum* spores will germinate in anaerobic conditions where there is available moisture and nutrients, and the acidity levels are low (pH > 4.5). Food products with pH > 4.5 are referred to as low acid foods, whereas products with pH values of 4.5 and below are referred to as acid, high acid or acidified foods. Chapters 4 and 5 describe the groups of foods that rely on acidity as a hurdle to microorganism growth. In the USA, the critical limit between acid and low acid foods is taken at pH 4.6 (<http://vm.cfsan.fda.gov/~comm/lacf-toc.html>). This critical pH limit is an important determinant as to whether heat-preserved foods receive a pasteurisation or sterilisation treatment.

It is also important to ensure that heat resistant spoilage organisms in acid foods do not cause the pH to shift above 4.5 and thereby allow the potential outgrowth of *C. botulinum* spores. This is known as metabiosis (Montville, 1982). It has been observed with post process contamination of tomatoes by moulds that elevate the pH and allow subsequent toxin production by *C. botulinum* (Huhtanen *et al.*, 1976; Odlaug and Pflug, 1978).

Although the mathematics of the minimum botulinum cook are given in various guideline documents (DoH, 1994), it is interesting to search out the background to where these recommendations

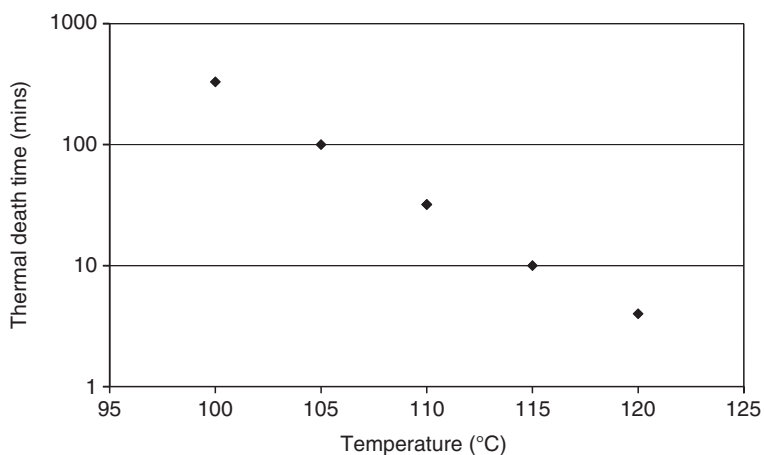


**Fig. 3.1** Maximum heat resistance data for *C. botulinum*, taken from Esty and Meyer (1922). Sixty billion spores in a phosphate buffer solution, pH 7.0.

first arose. The  $F_03$  process actually relates to thermal death kinetic work carried out by researchers in the USA between 1921 and 1950. The original death kinetics work often quoted is that of Esty and Meyer (1922), who investigated the death kinetics of *Bacillus botulinus* (then name for *C. botulinum*). The most prominent of their data was that for the maximum heat resistance, referred to as the terminal death time, for *B. botulinus* grown under optimum conditions. They started with an initial population of approximately 60 billion spores and thermally processed until a negative result was obtained, i.e. all the spores were destroyed and no out-growth resulted. This number of spores represents the maximum number they could fit into a 1 mL container; in effect there was nothing present but spores. Note that 60 billion refers to US billion ( $10^9$ ), which is  $60 \times 10^9$  spores. Results of maximum heat resistance to moist heat for the most resistant strain of *B. botulinus* were reported as follows:

4	minutes at 120°C	(248°F)
10	minutes at 115°C	(239°F)
33	minutes at 110°C	(230°F)
100	minutes at 105°C	(221°F)
330	minutes at 100°C	(212°F)

In the original paper, the above data were plotted, as shown in Fig. 3.1, but the data can also be converted to a logarithmic



**Fig. 3.2** Maximum heat resistance data for *C. botulinum*, taken from Esty and Meyer (1922). Sixty billion spores in a phosphate buffer solution, pH 7.0. Data plotted with thermal death time on a logarithmic axis.

thermal death axis, giving the more conventional approach shown in Fig. 3.2.

Several years later, Stumbo (1949) took information from the Esty and Meyer (1922) work for the thermal death time data and summarised it using the more familiar concepts of time at a given temperature. He found that an F value of 2.78 minutes was required at 250°F to process the spores to the point at which none survived. In effect, this was the time to destroy  $6 \times 10^{10}$  spores at 250°F (121.1°C) or to achieve almost 11-log reductions of *C. botulinum* spores. Thus, a safe assumption is to process to at least one more log reduction than is required, and so the F value of 2.78 minutes was increased to 3 minutes, which is the likely basis of the  $F_03$  value used widely today. We now use 0.21 minutes for the time required to achieve 1-log reduction in *C. botulinum* spores at 121.1°C, and so the 12-log reduction requires  $12 \times 0.21 = 2.52$  minutes, which is rounded up to 3 minutes.

### 3.4 COMMERCIAL STERILISATION

Any low acid food that achieves an  $F_03$  process is referred to as commercially sterile and will have a long ambient shelf-life. The term ‘commercially sterile’ is commonly used for low acid foods; however both pasteurised and sterilised foods are considered commercially sterile because of the caveat regarding the

**Table 3.1** Heat resistance data for spoilage microorganisms relevant to low acid foods. Data was extracted from Holdsworth (1997).

Microorganism	Temperature range studied (°C)	D <sub>121.1</sub> (seconds)	z-value (°C)
<b><i>C. botulinum</i></b>			
(Phosphate buffer)	104–127	8.0	9.0
(Water)	104–127	3.1	8.5
(Pureed peas)	104–127	5.3	8.3
(Meat and vegetables)	100–113	6.6	9.8
(Seafood)	100–113	3.0	7.4
(Poultry)	100–113	3.0	7.4
(Rock lobster)	105–115.5	18.0	10.8
<b><i>Bacillus stearothermophilus</i></b>			
(Phosphate buffer)	100–140	149	14.3
	100–140	170	12.3
	100–140	226	11.7
<b><i>Bacillus subtilis</i></b>			
(Phosphate buffer)	127–144	28.8	9.4
<b><i>Clostridium sporogenes</i></b>			
(Phosphate buffer)	100–120	15.0	9.1
(Strained pea)	115.5–143.3	60.0	9.8

microorganisms deemed ‘capable of growing in the food’. One of the definitions of commercial sterility is given by the UK Department of Health (DoH, 1994):

Commercial sterility is the condition achieved by the application of heat, which renders food free from viable microorganisms, including those of known public health significance, capable of growing in the food at temperatures at which the food is likely to be held during distribution and storage.

An  $F_0 3$  process will be safe with respect to *C. botulinum* spores but it is important to remember that the product may contain a small number of surviving spores of more heat resistant spoilage microorganisms. This is because there are many more types of spoilage microorganisms than those that cause concern for public health, and therefore it would be expected that a greater range of heat resistance is found. Table 3.1 presents published data on a selection of relevant spoilage organisms, including some data for *C. botulinum* spores.



Data in Table 3.2 is intended to illustrate two main points. The first is that *C. botulinum* spores show a range of heat resistance values and the value chosen for the minimum botulinum process is towards the higher end, but not at the higher limit. The second is that there are other heat resistant organisms likely to be found in low acid foods, and although they are not pathogenic organisms, they can still spoil the food.

Thus, the high D-values in Table 3.2 show that it is not possible to kill all microorganisms present in a food product without giving the food a very long process and rendering it commercially unpalatable. In practice, the food manufacturer makes a decision on the level of commercial risk with the applied thermal process, taking into account the likely spoilage microorganisms present in the raw materials. For example, a simple canned food such as canned carrots will contain few ingredients (carrots, water) and so the chance of contamination from heat resistant spoilage organisms is low. This is an example of a relatively pure product and it is acceptable to use a process close to the minimum botulinum cook value of  $F_0 3$ , perhaps  $F_0 4$  to  $6$  at the end of the heating phase. On the other hand, a formulated soup made from vegetables, starches and flavourings is likely to contain spores of heat resistant organisms present with the starches and flavourings. Operating close to  $F_0 3$  will result in the occasional spoilt batch of product and so it is typical for formulated products and recipe dishes to work towards higher  $F_0$  values such as  $8$  to  $10$  at the end of the heating phase.

The sterilisation process of  $F_0 3$  has been in operation for almost 100 years and with no known cases of *C. botulinum* poisoning from correctly applied processes. It is not intended to take into account spoilage organisms because of the wide variety that exist and the specific nature of the raw materials on which they are found. While the  $F_0 3$  concept is not perfect, it has served the industry well. The next section looks at the theory behind how bacterial spores are killed by heat and the models used to calculate their destruction.

### 3.5 MICROORGANISM DEATH KINETICS

Death of bacteria by moist heat is assumed to be almost logarithmic (Ball and Olsen, 1957; Stumbo, 1965), i.e. it follows first-order reaction kinetics in which the rate of decomposition is directly proportional to the concentration (Equation 3.1). There are many debates amongst the academic community as to whether first-order kinetics

is appropriate. However, for practical purposes the thermal processing sector continues to use first-order kinetics for two main reasons:

- (i) There is an overwhelming body of evidence to suggest that correctly applied thermal processes have not resulted in food poisoning incidents arising from *C. botulinum* spore survival. Note that all *C. botulinum* incidents have been traced back to post-process recontamination or the wrong process being applied. Hence, first-order kinetics has served the industry well for almost 100 years and will do so for many years to come.
- (ii) Applying a higher-order reaction rate to time and temperature data is considerably more complicated than for first-order kinetics. It could require a different approach to process validation work.

First-order reaction kinetics are therefore used for calculating integrated F-values. Equation 3.1 describes the rate of change in concentration (or numbers  $N$ ) of microorganisms with time ( $t$ ), where ( $k$ ) is the proportionality constant:

$$-\frac{dN}{dt} = kN \quad (3.1)$$

or

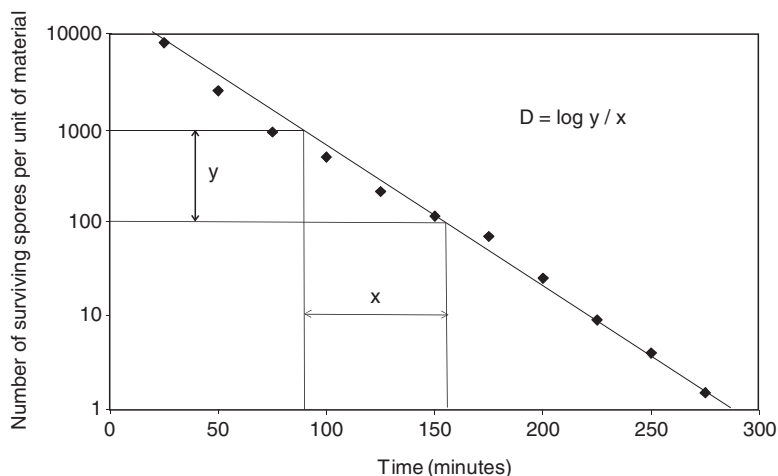
$$-\frac{dN}{N} = k \cdot dt \quad (3.2)$$

Integrating Equation 3.2 between the limits of  $N_0$  at time zero (the initial number of microorganisms per unit mass or volume) and  $N$  after a time of heating,  $t$  (the final number of microorganisms per unit mass or volume) results in Equation 3.3:

$$k = \frac{\ln(N_0 - N)}{t} \quad (3.3)$$

This is usually expressed using base ten logarithms ( $\log_{10}$ ), which are referred to in the remaining text without the subscript ( $\log$ ). Hence, Equation 3.3 becomes:

$$k = \frac{2.303 \log(N_0 / N)}{t} \quad (3.4)$$



**Fig. 3.3** Example of a first-order or logarithmic survivor curve, showing the calculation of decimal reduction time ( $D$ ), the time required to decrease the concentration of organisms by a factor of ten.

The conventional microbiological approach to quantifying thermal processing uses the decimal reduction time ( $D_T$ ), which is defined as the time required to destroy 90% of the organisms by heating at a single reference temperature ( $T$ ). This is calculated by the time required to traverse one log cycle on a microorganism survivor curve, as shown in Fig. 3.3.

Substituting terminology from microbiological death kinetics into the general equation for the straight line Fig. 3.3, Equation 3.5 is obtained.

$$\log N_0 - \log N = \frac{t}{D_T} \quad (3.5)$$

or

$$t = D_T \cdot \log \left( \frac{N_0}{N} \right) \quad (3.6)$$

By comparing Equations 3.4 and 3.6, the decimal reduction time and proportionality factor can be equated. Decimal reduction time is the more convenient term used in thermal processing:

$$D_T = \frac{2.303}{k} \quad (3.7)$$

Equation 3.6 presents the heating time ( $t$ ) needed at a constant reference temperature in order to reduce the number of microorganisms from their initial population ( $N_0$ ) to a final population ( $N$ ). This heating time is also referred to as a sterilisation or F-value, and represents the target number of minutes at temperature ( $T$ ) to achieve the desired log reduction in microorganisms (Equation 3.8).

$$F = D_T \cdot \log\left(\frac{N_0}{N}\right) \quad (3.8)$$

Thus, for a sterilisation process where 12-log reductions are required, the target F-value for an organism with a D-value of 0.3 minutes at 121.1°C is 3.6 minutes. As given earlier, the conventional approach in the UK (DoH, 1994) uses a D-value of 0.21 minutes at 121.1°C for *C. botulinum* spores, which equates to a minimum F-value of 2.52 minutes. For convenience, this is rounded up to 3 minutes.

### 3.6 LOG REDUCTIONS

It was stated earlier in this chapter that 12-log reductions should be achieved for the complete destruction of mesophilic strains of *C. botulinum* spores. Table 3.2 provides process times at 121.1°C required to achieve the 12-log reduction in *C. botulinum* spores in addition to the same information for certain spoilage organisms of greater heat resistance.

The organisms in Table 3.2 are by no means the most heat resistant that can be found in low acid foods. However, they are used to illustrate that a 12-log reduction in a spoilage organism such as *C. sporogenes* will require an excessive process time that will be detrimental to the food quality. Put another way, an  $F_03$  process will not be sufficient to achieve 12-log reductions in any of the spoilage organisms in Table 3.2.

Commercial practice is to use a lower number of log reductions for spoilage organisms, because the 12-log scenario deals with the extreme condition in which a food is contaminated at its maximum physical level. This is not an unreasonable approach for the lethal *C. botulinum* organism, because food products contaminated with botulism toxin result in human deaths and usually bankruptcy for the manufacturer. There may nowadays be a prison sentence for those deemed responsible. Spoilage outbreaks differ

**Table 3.2** Process times at 121.1°C to achieve 12-log reductions in spores of *C. botulinum* and selected spoilage organisms of greater heat resistance.

Microorganism	Medium	D <sub>121.1</sub> (seconds)	D <sub>121.1</sub> (minutes)	Time for 12-log reduction (minutes)
<i>C. botulinum</i>	Pureed peas	5.3	0.09	1.1
	Meat/vegetables	6.6	0.11	1.3
	Seafood	3.0	0.05	0.6
	Poultry	3.0	0.05	0.6
	Rock lobster	18.0	0.30	3.6
<i>B. subtilis</i>	Phosphate buffer	28.8	0.48	5.8
<i>B. stearothermophilus</i>	Phosphate buffer	149	2.48	29.8
<i>C. sporogenes</i>	Strained pea	60.0	1.00	12.0

markedly in that, whilst undesirable, the impact is significantly less. They result in commercial losses from recalled products and damage to the brand image; however, manufacturers can survive these situations.

The reality with spoilage incidents is that the actual numbers of likely organisms present in the food immediately prior to the process are taken into account. Final numbers of organisms must be sufficiently low that there are minimal chances of survivors (see Worked examples 3.1 and 3.2).

**Worked example 3.1** *C. sporogenes*

Measured D<sub>121.1</sub> value of 1.0 min.  
Initial numbers of spores (N<sub>0</sub>) is 850 per g of food.  
To ensure removal of spores, it is necessary to process until < 1 spore remains viable at the end of the process (N).  
Equation 3.6 can be re-written using the above data to calculate the process time (t) to achieve the above condition:

$$t = 1.0 \log \left( \frac{850}{1} \right) = 2.93$$

Hence, the process time required to eliminate these spores is a minimum of 2.93 min. Note that this does not allow margins for variability.

**Worked example 3.2** *B. stearothermophilus*

Measured  $D_{121.1}$  value of 2.48 min.

Initial numbers of spores ( $N_0$ ) is 1100 per g of food.

To ensure removal of spores, it is necessary to process until  $<1$  spore remains viable at the end of the process ( $N$ ).

Equation 3.6 can be re-written using the above data to calculate the process time ( $t$ ) to achieve the above condition:

$$t = 2.48 \log \left( \frac{1200}{1} \right) = 7.64$$

Hence, the process time required to eliminate these spores is a minimum of 7.64 min. Note that this does not allow margins for variability.

Calculations on actual reductions in spoilage organisms, as shown in the above worked examples, suggest that the required number of log reductions can be less than 12. In practice it is common to use log reductions between 4 and 5, typically 5. For the heat resistance values given in Table 3.2, *C. sporogenes* and *B. stearothermophilus* require process times (equivalent at 121.1°C) of 5 and 12.5 minutes, respectively to achieve the 5-log reduction. If the process times cannot be achieved without detriment to the product quality or cause production losses, it is necessary to investigate how the initial number of organisms can be reduced.

Chapter 9 also discusses log reductions in microorganisms, but from a process validation perspective when using a log reduction method. It introduces the idea of defining a starting number of microorganisms per unit mass of food and processing until the risk of survivors is vanishingly low.

There is an interesting difference in the numbers of log reductions required for pasteurised and sterilised foods. A pasteurisation process usually operates to 5 or 6 log reductions of the target organism (Campden BRI, 1992, 2006), and this differs from sterilised foods where the intention is to achieve at least 12-log reductions in *C. botulinum* spores. The lower log reduction for pasteurisation has evolved because of the reduced risks associated with the target microbial species when compared with the lethal botulinum toxin. Many of the early pasteurisation processes were spoilage processes, and so the mathematics were similar to those

presented above for the spoilage risks to sterilised foods. For example, with fruits with high levels of natural acidity, spoilage from yeast and mould is relevant, which is a much reduced risk than with a food safety organism such as *C. botulinum*. This justified the decision to reduce the population of yeast and mould by only 6-log reductions. With pasteurised foods, there is also the protection offered by the presence of additional preservation hurdles such as acidity, low water activity and low temperature storage.

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## 4 Acid and High Acid Foods

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### 4.1 BACKGROUND

*Clostridium botulinum* is the most heat resistant spore-forming bacteria known to produce a lethal toxin, but it cannot germinate or grow below pH 4.5. *Bacillus cereus* is another toxin-producing spore-former, but it is also sensitive to pH. Other organisms of concern with regard to food poisoning, for example *Listeria monocytogenes*, *Salmonella*, *Escherichia coli* O175, *Staphylococcus aureus* and *Campylobacter*, are all sensitive to mild heat treatment. However, there is a host of spoilage organisms (capable of producing gasses, taints or enzymes that can degrade the texture of the food) that are sensitive to pH and heat to differing degrees. The mild thermal process chosen must therefore take into account the actual pH of the product, as well as the kinds of microorganisms that are most likely to contaminate that product.

An acidity level of pH 4.5 will inhibit the growth of most spore-forming bacteria, and specifically *C. botulinum*. A mild heat treatment of 70°C for a few minutes will kill off all vegetative organisms, but not the bacterial spores. It must be noted that at a pH of 4.2 to 4.5 there is a risk of *C. botulinum* outgrowth if other spoilage organisms are able to grow and elevate the pH from their metabolic by-products. This risk is more of a concern in acidified foods.

Acid foods typically have a shelf-life of 1 to 3 years. The end of the shelf-life is often determined by:

- *Texture*: the natural acidity can chemically cause the cell walls to weaken and for there to be a gradual loss of texture.
- *Colour*: often products in this group will darken if exposed to light, as when packed in glass or clear plastic.



**Table 4.1** pH values of some fruits.\*

<b>Fruit</b>	<b>pH</b>	<b>Fruit</b>	<b>pH</b>
<i>Pome Fruits</i>		<i>Stone Fruits</i>	
Apple	3.3–3.9	Peaches	3.6–4.1
Pear	3.6–4.2	Apricots	3.4–3.8
<i>Citrus Fruits</i>		Cherries	3.2–4.5
Grapefruit	3.0–3.7	Plum	2.8–3.0
Orange	3.0–3.5	<i>Tropical Fruits*</i>	
Lemon	2.2–2.4	Pineapple	3.2–4.0
<i>Soft Fruits</i>		Mango	5.8–6.0
Strawberry	3.3–3.9	Litchi	4.7–5.0
Blackberry	3.9–4.5	Guava	3.8–4.4
Raspberry	3.2–3.6	Granadilla (Passion fruit)	3.3–3.6
Blueberry	3.1–3.4	Papaya	5.2–6.0
Gooseberry	2.8–3.1	Banana	4.5–5.2
Cranberry	2.3–2.5	Jams	3.3–3.7
Tomatoes	4.0–4.6		

\* Some of the tropical fruits have relatively high pH, and are actually classed as acidified products.

- *Tin pick-up*: products in this group are often packed in internally plain (unlacquered) cans to enhance their bright fruity colour (see discussion below).

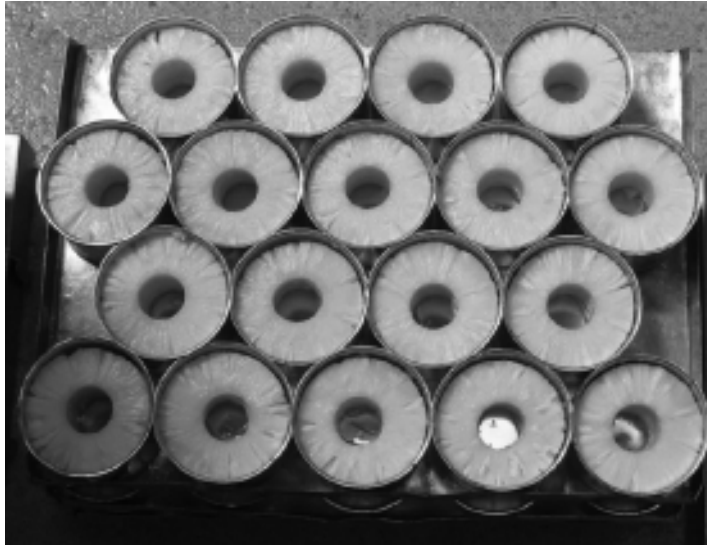
### 4.1.1 Naturally acid foods

The most frequently found products in the naturally occurring acid and high acid group include most canned fruit and fruit juices, tomatoes and jams. Table 4.1 presents pH information of many of the fruits used in canning.

## 4.2 THERMAL PROCESSING OF FRUIT

Canned fruit is usually processed in hot water or steam, because the acidity of the fruit allows a milder pasteurisation process. Some fruits are more sensitive to heat than others and therefore the selection and control of processing temperature is very important in determining the quality of the final product. As most of the thermal processes discussed in this chapter are below 100°C, for very heat sensitive products it is best to choose hot water as the processing medium, because the heat transfer is gentler than from steam.

The heat resistance of most microorganisms is closely linked to pH; the lower the pH, the more sensitive the microorganisms are



**Fig. 4.1** Pineapple packed in internally plain cans.

to heat destruction. Although the pH of products discussed in this group can go as high as about pH 5, it is often more effective to acidify the product to  $\text{pH} < 4.2$  or even  $< 4.0$ . Citric acid is most commonly used for this purpose, as it imparts only a slight fruity flavour and is relatively inexpensive.

### **4.3 PACKAGING SELECTION**

The most common type of packaging for high acid fruits is tin-plate cans. Fruit can also be packed in plastic (HDPE, PP or multilayer) tubs or in glass. However, one of the factors that can limit the shelf-life of fruits packed in plastic is the barrier properties of the plastics, and specifically its ability to limit oxygen ingress.

A factor that limits the shelf-life of fruits packed in metal cans is the colour of the fruit. Internally plain cans are used to pack 'white' fruit (e.g. pears, peaches, apricots, pineapples and citrus) as the product has a much superior colour when compared with the same product packed in internally lacquered cans (Fig. 4.1). In lacquered cans, white fruit tends to darken, and the end of the shelf-life is usually determined by an unacceptably dark colour after 18 to 24 months. This darkening is caused by oxidation reactions.

### 4.3.1 Oxidation reactions inside an internally plain can of acid fruit

When these acidic fruits are packed in plain tinplate cans, a reducing environment is created when tin, from the tinplate, is dissolved in the acids from the fruit. The hydrogen ions ( $H^+$ ) from the acid, instead of reacting with other compounds of the fruit and causing discolouration, react with the electrons from the tinplate and hydrogen is formed. This reducing environment restricts the oxidation-type reactions that cause colour and flavour changes. This system works very well to maintain the bright colour of 'white' fruits (such as those mentioned above), but can cause the pigments of some fruits, such as strawberries or cherries, to lose their colour.

A disadvantage of using plain cans is that the product picks up tin over time. The tin pick-up rate is difficult to accurately predict, as there are many factors that can influence it.

In general, in the first month after canning, 10 to 20 ppm of tin is dissolved by the product. Thereafter, tin is dissolved at a rate of 2 to 4 ppm per month. The maximum permissible amount of tin allowed in canned fruit is 200 ppm in most countries, but can vary from 150 to 250 ppm, depending on the legislation of the particular country.

Factors that can affect the rate of tin pick-up include the amount of oxygen in the can, the temperature of storage, the length of storage, and the presence of de-tinning accelerators. When using internally plain cans, good manufacturing practices include:

- packing the can with a high vacuum ( $>30\text{ kPa}$ );
- packing the can with a low to moderate headspace (4–8 mm);
- controlling delays during packing. For example, delays after syrupe and before seaming can result in de-tinning at the headspace interface as a result of the oxygen from the atmosphere reacting with the tin and the product;
- storage at a low temperature ( $<20^\circ\text{C}$ ), because a high temperature accelerates the corrosion reactions;
- controlling product quality so that compounds such as sulphur dioxide, nitrates and copper are avoided, because they can all accelerate corrosion.

Fruits that benefit from being packed in internally plain cans are pears, peaches, apricots, pineapples and citrus.

### 4.3.2 Pigments that discolour in internally plain cans

The pigment anthocyanin, which gives many berry fruits their blue/red colour, is sensitive to the reducing environment created inside the plain can and becomes colourless in this environment.

Anthocyanin is also a de-tinning accelerator and will speed up the rate of de-tinning, and thus shortening the shelf-life. For these reasons, berry fruit and fruits with red colour are not packed in internally plain cans.

## 4.4 DETERMINING PROCESS RECOMMENDATIONS FOR ACID FOODS

Pasteurisation is a relatively mild heat treatment that is applied to acid foods, whereas sterilisation processes are aimed at destroying all pathogenic microorganisms and their spores. Pasteurisation processes are designed to eliminate vegetative spoilage microorganisms that are not very heat resistant, and the low product pH inhibits the growth of any surviving microorganism and prevents spores germinating. Pasteurisation also inactivates enzymes, naturally present, that could cause chemical deterioration of the product on storage.

The mathematical theory of pasteurisation is the same as for sterilisation, but the target microorganisms that populate acid foods are less heat resistant and so effectively the reference temperatures ( $T_{ref}$ ) and z-values used are different. Some pasteurisation processes are described by Pasteurisation Units (PU), similar to the  $F_0$  value for a low acid product. PU are also referred to as P-values but the meaning is identical. The PU was originally designed for the pasteurisation of beer, where it has a reference temperature of 60°C and a z-value of 7°C.

Calculation of pasteurisation units is useful to give the process a reference thermal exposure, but there is no international minimum as there is for low acid canned foods (i.e.  $F_0 3$ ). However, there are some general guidelines, but for many canned acid foods, the processes are designed so that a minimum temperature is achieved at the coldest part of the product.

Controlling the product pH is critical so that the types of microorganisms that can grow in the food are also controlled. Table 4.2 presents the minimum growth pH for some of the microorganisms of concern for acid foods.

### 4.4.1 Calculation of pasteurisation values

The aim of pasteurisation is to reduce the number of pathogenic and spoilage organism by a specific amount; usually 6 log reductions. This, together with the hurdle of low pH should be sufficient to ensure that a satisfactory shelf-life is attained. The death kinetics

**Table 4.2** Limiting pH values for growth of microorganisms of concern in the acid foods group (taken from Campden BRI, 1992).

Organism	Minimum growth pH	Other factors	Medium/Substrate
<i>Bacillus licheniformis</i>	4.2		Tomato puree
<i>Clostridium butyricum</i>	4.0		Canned mung beans
<i>Clostridium pasteurianum</i>	3.8	$a_w$ 0.98–0.99	Mango preparation
<i>Clostridium pasteurianum</i>	4.1	$a_w$ 0.975	Mango preparation
<i>Clostridium barati</i>	3.7		Canned mung beans
<i>Bacillus coagulans</i>	3.85		Tomato juice
<i>Bacillus polymyxa</i>	3.8–4.0		Sucrose nutrient broth
<i>Bacillus macerans</i>	3.8–4.0		Sucrose nutrient broth
<i>Lactobacillus brevis</i>	3.5		Citrus fruit
<i>Aspergillus</i> spp.	2.0		Laboratory media
<i>Fusarium</i> spp.	2.0		Laboratory media
<i>Penicillium</i> spp.	2.0		Laboratory media

of spores and vegetative cells ( $D$ - and  $z$ -values) represent the heat resistance of particular organisms, and are affected by the environment (product type) that they are in. Thus, the lethal effect of heat exposure can be enhanced, reduced or synergised by the presence of sugars, acids, fats and even the concentration of the specific product in question. Tables 4.3, 4.4 and 4.5 present a selection of industrially relevant data for pasteurisation processes. Much of this was taken from Campden BRI guidelines (Campden BRI, 1992, 2006).

The data on the heat resistance are usually taken from work done and published by researchers, as it usually is impractical to determine the  $z$ -value required to calculate a process by doing the microbiology. Using the values from the literature, the time required to process a product to achieve a specific reduction in microbial load can be calculated. The method uses an equation first published by Stumbo in 1973 (Equation 4.1):

$$F = D_T \cdot \log 10^n \quad (4.1)$$

where  $F$  is the required lethality of the process (minutes),  $D_T$  is the  $D$ -value at the reference temperature,  $T_{ref}$  (minutes) and  $n$  is the number of log reductions required (usually 6).

Once the lethality required has been calculated, the equivalent process at other temperatures can be calculated, using Equation 4.2:

$$L = \log 10^{-1} ((T - T_{ref})/z) \quad (4.2)$$

**Table 4.3** Heat resistance data for Bacilli and Clostridia applicable to pasteurised products.

Organism	Heating substrate	Heating temperature (°C)	D-value (minutes)	z-value (°C)
<i>B. cereus</i>	Buffer (pH 7.0)	100	8.0	10.5
<i>B. coagulans</i>	Buffer (pH 4.0)	98.9	9.5	–
<i>B. coagulans</i>	Buffer (pH 4.5)	110	0.64–1.46	–
<i>B. coagulans</i>	Buffer (pH 4.2)	110	0.56–10.6	–
<i>B. coagulans</i>	Red pepper (pH 4.5)	100	5.5	–
<i>B. coagulans</i>	Buffer	106	6.3–7.3	8.2–9.6
<i>B. licheniformis</i>	Buffer (pH 4.0)	100	1.05	10.2
		105	0.19	
		110	0.12	
<i>B. licheniformis</i>	Buffer (pH 7.0)	100	4.29	8.1
		105	0.98	
		110	0.27	
<i>B. polymyxa</i>	Buffer (pH 7.0)	100	18 (approx)	–
<i>B. subtilis</i>	Buffer (pH 6.8)	121	0.57	9.8
<i>C. botulinum</i>	Buffer (pH 7.0)	82.2	32.3	69.7
non-proteolytic type B				
<i>C. botulinum</i>	Water	80	3.3	9.4
non-proteolytic type E				
<i>C. butyricum</i>	Buffer (pH 7.0)	85	23	–
<i>C. butyricum</i>	Peach	90	1.12	11.5
<i>C. pasteurianum</i>	Buffer (pH 4.5)	95	3.95	–
<i>C. tyrobutyricum</i>	Buffer (pH 7.0)	90	18	–

**Table 4.4** Heat resistance data for other bacteria applicable to pasteurised products.

Organism	Heating substrate	Heating temperature (°C)	D-value (minutes)	z-value (°C)
<i>Enterococcus (Strep) faecalis</i>	Fish	60	15.7	6.7
<i>E. coli</i>	Broth	56	4.5	4.9
<i>Lactobacillus plantarum</i>	Tomato juice	70	11	12.5
<i>L. plantarum</i>	Buffer (pH 4.0)	50	1.81	6.45
<i>L. plantarum</i>	Buffer (pH 7.0)	55	3.64	6.1
		60	0.20	
		65	0.05	
		70	0.02	
<i>Listeria monocytogenes</i>	Carrot	70	0.27	6.7
<i>Pseudomonas fluorescens</i>	Broth	60	3.2	7.5
<i>Salmonella senftenberg</i>	Pea soup	60	10.6	5.7
<i>S. aureus</i>	Pea soup	60	10.4	4.6

**Table 4.5** Heat resistance data for other yeasts and moulds applicable to pasteurised products.

Organism	Heating substrate	Heating temperature (°C)	D-value (minutes)	z-value (°C)
<i>Byssoschlamys fulva</i>	Grape drink	93	5.0	7.8
<i>Saccharomyces cerevisiae</i> (ascospores)	Buffer (pH 4.5)	60	22.5	5.5
<i>Zygosaccharomyces bailii</i> (vegetative cells)	Buffer (4.5)	60	0.4	3.9
<i>Z. bailii</i> (ascospores)	Buffer (4.5)	60	14.2	3.9
<i>Z. bailii</i> (ascospores)	Broth	60	8.1	5.0

where  $L$  is the lethal rate (equivalent to a P-value of 1 min at  $T_{ref}$ ),  $T$  is the temperature under consideration (°C),  $T_{ref}$  is the reference temperature (°C) and  $z$  is the z-value of the organism under consideration (°C).

Therefore Equation 4.3 is used to calculate the required number of minutes to process at the chosen temperature, to achieve the required lethality ( $L$ ):

$$\text{Process Time} = F/L \quad (4.3)$$

## 4.5 INHIBITORY FACTORS TO MICROORGANISM GROWTH

As mentioned previously, the efficacy of heat in destroying organisms is influenced by various factors. It is for this reason that mild heat alone cannot be used to produce safe stable pasteurised foods. The most common factors used in conjunction with heat are pH, undissociated organic acids, water activity and low temperature storage. Even if an appropriate heat treatment is applied at the desired level, if these other factors are not in control, there is the potential for microorganisms to grow and spoil the food.

The following statements are usually true:

- Most spore-forming bacteria are inhibited by a combination of  $\text{pH} < 4.6$  and  $a_w < 0.90$ .
- Acid tolerant spore-forming bacteria will survive and grow at pH greater than 3.8. This includes many of the butyric anaerobes, a group of bacteria that under anaerobic conditions can ferment sugars to butyric acid, and includes *B. macerans* and *B. polymyxa*.

- Some xerophilic, osmophilic, spore-forming yeasts and moulds can grow below  $a_w$  0.85.
- Anti-mycotic agents (preservatives) have been successfully used in foods to prevent the outgrowth of yeasts and moulds.
- *C. botulinum* does not usually germinate and grow in foods with a pH of <4.5 or a water activity ( $a_w$ ) of <0.94, although some experimental conditions have shown growth and toxin production by *C. botulinum* at pH<4.5 (Raattjes and Smelt, 1979).
- Chilling is only a short-term barrier to microbial growth.

It should be noted that the thermal destruction of some yeasts and moulds is more complex than simple logarithmic destruction. Ascospores can become activated at temperatures as high as 85°C. Unusual heat resistance was reported in pasteurised beverages and sauces that contained ascospores of *Talaromyces trachyspermus* and *Neosartorya fisheri* (Campden BRI, 1992).

In a product where the pH is less than 3.8, there is very low risk of germination and outgrowth of bacterial spores, but certain yeasts and moulds can thrive. The heat process for food pH<3.8 therefore only needs to be designed to destroy those yeasts and moulds. In products with pH>3.8, other organisms are capable of surviving, and so the heat process applied must be sufficient to ensure that their numbers are destroyed. As a generalisation, within the acid foods group, products can be further divided into pH categories so that a minimal but effective heat treatment can be applied.

#### **4.5.1 High acid: pH < 3.8**

This group includes cherries, plums, apricots, berries, citrus and sometimes pineapples (Table 4.1). The spoilage organisms include yeasts, moulds and lactic acid bacteria. Due to the high acidity of these fruits, they generally are very susceptible to softening during heat processing, and processors usually try to process them as close to the minimum requirement as possible. As this group is very susceptible to heat damage, it is advisable to process in water as the rate of heat transfer is lower than through steam, and so is gentler on the product (see Examples 4.1 and 4.2).

Process recommendations for highly acid products sometimes target a can centre temperature (CCT) in the 70°C's, with a holding time of 2 to 3 minutes, but practically a CCT of 80 to 82°C is usually targeted for most products in this group.



**Example 4.1** Apricot softening

Softening of apricots is sometimes found in canned apricots. This can be caused by enzymatic softening due to contamination by one of two moulds; *Byssoclamys* produces heat stable ascospores that can germinate after processing, or *Rhizopus* that produces a heat stable enzyme, that even though the mould itself may be destroyed during processing, is heat stable enough to cause softening of the fruit. The softening can also be caused by acid in the fruit causing the cell walls to disintegrate during and after processing.

**Example 4.2** Processing of grapefruit

Grapefruit is a highly acidic product (pH 3.0–3.3) that is very heat sensitive. Segments must be prepared using either chemical or manual processes. No agitation during cooking is recommended. Low process temperatures are preferred and a minimum CCT of 80°C is targeted. After processing, the best quality products are achieved if there is efficient cooling (Fig. 4.2).



**Fig. 4.2** Grapefruit cannery.

Ascospores of *B. fulva* or *B. nivea* can survive this process and good hygiene in production is essential to ensure that they are not present in the canned product, because if they grow, they can produce enzymes that can soften the fruit.

#### **4.5.2 Acid: pH 3.8–4.2**

This group of fruits includes peaches, apples and pears (Table 4.1). General process recommendations are for the CCT to reach 85°C for 5 minutes or 95°C for 30 seconds (see Examples 4.3 and 4.4). This is effectively a P-value of 5 minutes at 85°C (PU 5). The process is intended to target spoilage organisms and includes yeasts, moulds, lactic acid bacteria and some acid tolerant bacteria,

##### **Example 4.3** Canning of peaches

The pH of peaches varies from 3.6 to 4.1. Canned peaches are processed in continuous cooker coolers with axial agitation. This results in good heat distribution and uniform cooking. CCT of 91°C minimum are used, even though most guidelines state that 85°C is sufficient.

##### **Example 4.4** Canning of pears

Pears are a difficult fruit to can because their ripening is unpredictable and so they must be held in cold stores for about 10 days or the texture will be variable. Also, the pH can be as high as 4.5 and so this must be monitored and the fruit acidified when necessary. It is recommended to acidify to pH 3.8–4.0, but it must be pH < 4.2. As with other fruits, hygiene is important to minimise spoilage. Processing to a minimum CCT of 96°C is recommended. Green fruit is significantly harder and takes longer to process. There is an under-processing risk if fruit of differing textures are processed together – as well as the other microorganisms that can cause spoilage in this group, spoilage by *C. butyricum* can be found.



**Fig. 4.3** Peaches being conveyed into a cannery.

for example *B. coagulans*. For all acid and high acid fruit products, good hygiene during product peeling and sorting is critical as many of the organisms that can spoil canned fruit are sufficiently heat resistant that they cannot be processed away without damaging the texture and colour (Fig. 4.3).

#### **4.5.3 Medium acid: pH 4.2–4.5**

This group includes tomatoes and some pears. The heat resistance of microorganisms is greater at the slightly higher pH and so processing to CCT of 100 to 104°C is recommended. If the fruit texture is unable to withstand this high process, the product must be acidified and a lower process applied (Fig. 4.4).

### **4.6 P-VALUE GUIDELINES**

Many of the fruits are very heat sensitive, and so the processes are often very close to the minimum P-value requirements. These are often established by trial and error, because the low pH ensures that food poisoning is not a risk with these products. Hence, the processes are based on spoilage and there are more variations in



**Fig. 4.4** Tomatoes being conveyed into the cannery.

the guidelines than are found with fully sterilised foods that must achieve  $F_0 3$ .

Products of different pH can support the growth of different spoilage organisms, and so different P-values are often used. The recommendations in Table 4.6 were taken from Eisner (1988). It is one of the few information sources that provide processes for products over a wide range of pH ( $2.5 < \text{pH} < 4.5$ ).

Another source of information is the National Food Processors Association (USA), which give the following recommendations for processing acid products that may contain butyric anaerobes (e.g. tomato).

For products between pH 4.0 and 4.3, the process should be equivalent to 5 minutes at 200°F (93.3°C):

P-value > 5 minutes ( $T_{\text{ref}}$  200°F,  $z$  15°F) or ( $T_{\text{ref}}$  93.3°C,  $z$  8.3°C)

For product between pH 4.3 and 4.6, the process should be equivalent to 10 minutes at 200°F (93.3°C)

P-value > 10 minutes ( $T_{\text{ref}}$  200°F,  $z$  15°F) or ( $T_{\text{ref}}$  93.3°C,  $z$  8.3°C)

**Table 4.6** Suggested P-values ( $T_{\text{ref}}$  93.3°C,  $z$  8.9°C) for fruit and vegetables (Eisner, 1988).

Product	pH	P-value (minutes)
Lemon juice	2.5	0.1
Plums	2.8	0.2
Gooseberries	3.0	0.5
Pickled vegetables	3.0	0.5
Greengages	3.2	0.8
Rhubarb	3.2	0.2–0.4
Mandarins	3.2–3.4	1.0–2.0
Grapefruit juice	3.2	0.2–0.4
Apricots	3.2–4.0	1.0–8.0
Apples	3.3	0.2–0.6
Blackberries	3.3	
Orange juice	3.5–3.8	0.2–0.6
Pineapples	3.5	0.6–0.8
Strawberries	2.3–4.0	0.8
Jams	3.5	0.8
Sour cherries	3.5	0.2–0.4
Sauerkraut	3.5–3.9	0.5
Pickled gherkins	3.5–3.8	0.5–1.0
Bilberries	3.7	0.5
Sweet cherries	3.8	0.6–2.5
Guavas	3.8	0.8
Nectarines	4.0	1.5–8.0
Peaches	4.0	1.5–8.0
Pears	4.0	1.3–10.0
Sweet and sour gherkins	3.6–4.1	0.5–1.0
Tomatoes	4.2–4.5	2.0–10.0
Tomato paste	4.2–4.5	1.0–5.0

## 4.7 GUIDELINES TO CRITICAL FACTORS IN THERMAL PROCESSING OF ACID FOODS

Although the numbers of microorganisms that can spoil acid and high acid foods are limited, and the risk of food poisoning from consumption of food from this group is low, commercial production of these products demands commercial sterility for economic reasons (see Example 4.5). The commercial sterility of acid and high acid products is dependent on many complementary factors that pertain to the product and to the processing. Critical factors (as defined by the FDA) are ‘any property, characteristic, condition, aspect or other parameter, which when varied may affect the scheduled process and the attainment of commercial sterility.’ Product and process related critical factors are many and include the following:

- microbial load/bio-burden;
- pH of the product;
- water activity;
- consistency;
- product composition/formulation, including sizes of solid ingredients;
- in-going weight of product(s), including liquor where appropriate;
- the presence (if any), concentration and types of preservatives;
- drained weight;
- headspace;
- the numbers and kinds of spoilage microorganisms;
- container size and geometry;
- container vacuum;
- processing method;
- type and characteristics of heat processing system;
- processing temperature;
- minimum initial temperature;
- processing time.

Small deviations from the product or process specification, which may seem negligible or insignificant, may seriously affect the adequacy of the process for that product, therefore any changes or deviations should be evaluated as to the effect on the adequacy of the process. This subject is considered in more detail in Chapter 9, on 'Measurement and validation of thermal processes'.

#### **Example 4.5** Thermo-tolerant aciduric spore-forming bacteria

*Alicyclobacillus* spp. are thermophilic, acid-tolerant, spore-forming, aerobic bacteria that are implicated in the spoilage of fruit juices and can cause spoilage in canned fruit and tomatoes. These bacteria are not a health risk, but cause spoilage by producing halogenated phenols (e.g. guaiacol) that cause taints at low concentrations. A typical description of a spoilage complaint is often as bitter, 'TCP', 'disinfectant', 'chemical'. Contamination from *Alicyclobacillus* is generally from the soil. The organisms cannot be successfully 'processed

away', as the temperature time combinations would damage the heat sensitive acid products, but should be eliminated by good hygiene. The bacteria are capable of growing at pH as low as 2.5. Two different species that have been found in food spoilage are *A. acidoterrestris* and *A. acidocaldarius*.

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## 5 Acidified Foods

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### 5.1 BACKGROUND

Acidified foods are low acid foods to which acid is added to reduce the pH to 4.6 or below (in the UK pH 4.5 is the value used). The foods have a water activity greater than 0.85 and are packaged in hermetically sealed containers. Fresh pack pickles are an example of acidified foods. Legislation states (Codex and FDA) that acidified foods shall be manufactured, processed and packaged so that a finished equilibrium pH value of 4.6 or lower is achieved within the time designated in the scheduled process and maintained in all finished foods. Acidified foods are thermally processed to an extent that is sufficient to destroy the vegetative cells of microorganisms of public health significance and those that can cause spoilage. Examples include fresh pack pickles, acidified peppers and cook-in sauces (Fig. 5.1).

*Clostridium botulinum* is an anaerobic microorganism, which is almost universally present. Under certain conditions *C. botulinum* can grow in foods and produce a powerful toxin that affects the nervous system. *C. botulinum* will only grow where there is an absence of oxygen, a 'favourable' pH and temperature, and sufficient water and nutrients necessary for its growth. Low-acid canned foods provide this favourable environment. When a product is acidified to a pH of 4.6 or less, *C. botulinum* cannot grow. The pH is critical and therefore a critical part of the manufacture of acidified products is control of the finished equilibrium pH.

The Codex Alimentarius *Code of Hygiene Practice* states that:

It should be emphasised that the acidification and heat processing of low-acid canned foods are very critical operations involving public health risks and appreciable losses of product if inadequately processed.





**Fig. 5.1** Pickled cucumbers ready to be processed.

The United States Food and Drug Administration (FDA) has defined an ‘acidified food’ as:

...a low-acid food to which acid/s or acid food/s has been added to the product to produce a finished equilibrium pH of 4.6 or below and a water activity greater than 0.85. Foods such as fresh packed pickles, peppers and marinated vegetables are acidified foods. Foods such as jams, jellies, carbonated beverages; acid foods such as condiments, sauces and dressings that contain small amounts of low acid foods with a resultant pH that does not differ significantly from the predominant acid or acid food ingredient; naturally acid foods like tomatoes are not considered to be acidified foods. Fermented foods (some of cucumber pickles, most green olives and sauerkraut) are not considered to be acidified foods because pH reduction is not accomplished by the addition of acids or acid foods.

## **5.2 ACIDITY MEASUREMENT USING pH**

### **5.2.1 The history of pH**

The term ‘pH’ is used to designate the intensity or degree of acidity. It was developed by a Danish scientist, Søren Peter Lauritz Sørensen in 1909. Until Sørensen developed the pH scale, there was no widely accepted way of expressing hydrogen ion concentrations. Sørensen suggested that the power could be represented by a pH scale in which 7 is neutral, and 1 and 14 are the extremes of acidity and alkalinity, respectively. The letters pH are an

abbreviation for ‘pondus hydrogenii’ (translated as potential hydrogen), meaning hydrogen power, as acidity is caused by a predominance of hydrogen ions ( $H^+$ ).

### 5.3 THE CHEMISTRY OF pH

pH is defined as the negative logarithm of the hydronium ion concentration or  $-\log[H_3O^+]$ . Pure water auto-ionises to produce equal concentrations of hydronium and hydroxide ions, as in Equation 5.1 (see Example 5.1):



This equilibrium obeys the law of mass action in the form:

$$K_w = [H_3O^+] [OH^-] = 1.0 \times 10^{-14} \text{ (at } 25^\circ\text{C)} \quad (5.2)$$

$K_w$  is an equilibrium constant for the chemical reaction,  $\text{mol}^2 \text{dm}^{-6}$ .

This ‘modern’ form of the equation for water auto-ionisation recognises that protons do not exist in solution but instead are bound to an electron lone pair in water, as in Equation 5.3:



The obsolete hydrogen ion term has been replaced by ‘hydronium ion’ but it is common practice to continue to use pH (and not  $pH_3O^+$ ). Since the hydronium ion concentration and the hydroxide ion concentration are equal in pure water, it follows that:

$$[H_3O^+] = [OH^-] = 1.0 \times 10^{-7} \quad (5.4)$$

#### **Example 5.1** Calculating the pH of a solution

Pure water is neutral and has a pH of 7.0. This indicates that the hydronium ion concentration is 0.0000001 g per litre, and so the  $pH = -\log(1.0 \times 10^{-7}) = 7.0$ .

In dilute acid solution, the hydronium ion concentration is higher, for example in a  $10^{-6}\text{M}$  solution,  $[H_3O^+] = 10^{-6} \text{ mol/L}$  so that the  $pH = 6.0$ . That is, one step lower, or higher on the pH scale, represents 10 times higher (or lower) hydronium ion concentration.

**Table 5.1** Concentration of  $[H_3O^+]$  and  $[OH^-]$  in various liquid foods at 25°C (taken from Nielsen, 2003).

Food	$[H_3O^+]$ (mol/L)	$[OH^-]$ (mol/L)	pH
Cola	$2.24 \times 10^{-3}$	$4.66 \times 10^{-12}$	2.65
Grape juice	$5.62 \times 10^{-4}$	$1.78 \times 10^{-11}$	3.25
Seven Up	$3.55 \times 10^{-4}$	$2.82 \times 10^{-11}$	3.45
Schiltz beer	$7.95 \times 10^{-5}$	$1.26 \times 10^{-10}$	4.10
Pure water	$1.00 \times 10^{-7}$	$1.00 \times 10^{-7}$	7.00
Tap water	$4.78 \times 10^{-9}$	$2.09 \times 10^{-6}$	8.32
Milk of Magnesia	$7.94 \times 10^{-11}$	$1.26 \times 10^{-4}$	10.10

The value of pH, the logarithm of the reciprocal of the hydronium ion concentration in solution, is determined by measuring the difference in potential between two electrodes immersed in a sample solution. A suitable system consists of a potentiometer, a glass electrode and a reference electrode. A precise pH determination can be made by making an electromotive force (emf) measurement of a standard buffer solution whose pH is known, and then comparing that measurement to an emf measurement of a sample of the solution to be tested. Table 5.1 presents examples of liquid foods of varying pH, showing that most are acidic.

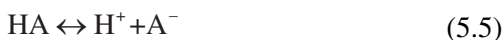
Acidification of foods requires that acids are added to foods to change the pH of that food. Acids can be divided into two groups: strong acids and weak acids. Weak acids are more common in Nature and are most important in acidification of foods because they are effective antimicrobial agents. Weak acids are mostly organic and include:

- benzoic acid;
- sorbic acid;
- propionic acid;
- lactic acid;
- citric acid.

Strong acids tend to be inorganic and less common in Nature. Some examples of strong acids are:

- hydrochloric acid;
- sulphuric acid;
- phosphoric acid.

Weak acids (HA) ionise in water and dissociate incompletely into positive and negative compounds; the hydronium ion and the conjugate base ( $A^-$ ), as given in Equation 5.5. For simplicity, the hydronium ion is represented by  $H^+$ .



The degree of dissociation into the positive and negative ions is a characteristic of different acids. When the amount of HA,  $\text{H}^+$  and  $\text{A}^-$  do not change, they are said to be in equilibrium. This is calculated using the dissociation constant ( $K_a$ ), which is written as the quotient of the equilibrium concentrations, as in Equation 5.6:

$$K_a = \frac{[\text{H}^+][\text{A}^-]}{[\text{HA}]} \quad (5.6)$$

A logarithmic measure of the acid dissociation constant is more commonly used in practice,  $\text{p}K_a$ , which is equal to  $-\log_{10} K_a$ , and is also referred to as the acid dissociation constant, as in Equation 5.7:

$$\text{p}K_a = -\log_{10} K_a \quad (5.7)$$

A high value of  $\text{p}K_a$  indicates a low level of dissociation of the acid into its constituent ions. A weak acid has a  $\text{p}K_a$  value in the approximate range  $-2$  to  $12$  in water. Acids with a  $\text{p}K_a$  value of less than about  $-2$  are said to be strong acids and are almost completely dissociated in aqueous solution, to the extent that the concentration of the undissociated acid becomes undetectable. Table 5.2 presents examples of  $\text{p}K_a$  values for some weak acids used in food preservation.

The pH of the aqueous solution will affect the concentrations of the undissociated and the dissociated acid, as in Equation 5.8:

$$\text{pH} = \text{p}K_a + \log [\text{A}^-]/[\text{HA}] \quad (5.8)$$

**Table 5.2** Table of  $\text{p}K_a$  for some weak acids.

Weak acid	$\text{p}K_a$
Acetic acid	4.75
Ascorbic acid	4.17
Benzoic acid	4.19
Citric acid	3.12
Lactic acid	3.86
Malic acid	3.40
Propionic acid	4.87
Sorbic acid	4.75

At pH values  $< pK_a$ , the equilibrium shifts to  $[HA]$  and at pH values  $> pK_a$ , the equilibrium shifts to  $[H^+]$  and  $[A^-]$ .

The undissociated form of the acid is more effective as an antimicrobial agent, hence weak acids used for food preservation are more effective at lower pH values.

## 5.4 MEASUREMENT OF pH

Some methods that may be used to determine pH or acidity for acidified foods include potentiometers, colorimetric and titration methods (see Examples 5.2 and 5.3).

### 5.4.1 Potentiometric method

The primary instrument for use in pH determination is the pH meter or potentiometer. The typical pH meter is equipped with a glass membrane electrode and a reference electrode or a single probe combination electrode. The most commonly used reference electrode is the calomel electrode, which incorporates a salt bridge filled with saturated potassium chloride solution. Calomel electrodes should be kept filled with saturated potassium chloride solution or other solution specified by the manufacturer, because they may become damaged if they are allowed to dry out. For best results, electrodes should be soaked in buffer solution, distilled or deionised water. Electrodes should be rinsed with water before immersing in

#### **Example 5.2** Measuring the pH of salad dressing

Separate out the oil and water phases (by centrifugation). Measure the pH of the aqueous phase only. It is not possible to measure the pH of oil. Measuring samples high in oil will affect the pH electrode and thus the pH measurement.

#### **Example 5.3** Measuring the pH of acidified bean salad

Separate out the solids and the liquid portions. Measure the pH of the liquid portion directly. Collect the solids (filter out on a screen). Wash with distilled water. Homogenise. Measure the pH, adding a little distilled water is required. The pH after processing should be  $\leq 4.6$ .



**Fig. 5.2** Beetroot in vinegar brine with temperature measuring probe at geometric can centre.

the standard buffers and rinsed with water or the solution to be measured next between sample determinations. To obtain accurate results, a uniform temperature should be maintained for the electrodes, the standard buffer solutions and the samples. Tests should be made at a temperature between 20 and 30°C, the optimum being 25°C. The accuracy of most pH meters is stated to be approximately 0.1 pH unit, and reproducibility is usually  $\pm 0.05$  pH units or less (Fig. 5.2)

#### 5.4.2 Colorimetric measurement

This method may be used instead of the potentiometric method, if the pH is 4.0 or lower. The colorimetric method for pH involves the use of indicator dyes in solutions that gradually change colour over limited pH ranges. An indicator that has the greatest colour change at approximately the pH of the sample being tested is selected. The pH is determined by the colour of the indicator when exposed to the sample under test.

A paper tape treated with indicator dye (indicator paper) is dipped into the sample solution, and depending upon the pH of the solution, the tape will change colour and an approximate pH can be determined by comparison with a standard colour chart. This method does not have the accuracy of the potentiometric method but can provide a quick test.

### 5.4.3 Titratable acidity

Titratable acidity is the least common method and requires the operator to perform tests to determine a correlation between pH and titratable acidity. Titratable acidity measures total available hydrogen ions in solution. This measurement includes both the free hydrogen ions and the undissociated hydrogen ions from acids that can be neutralised by sodium hydroxide. It is usually performed in a laboratory because of access to equipment.

## 5.5 ACIDIFICATION OF FOODS

The natural buffering capacity of most foods naturally opposes acidification. Methods of acidification to reach an acceptable equilibrium pH level in the final product are many and include:

- blanching of the food ingredients in acidified aqueous solutions;
- immersion of the blanched food in acid solutions;
- direct batch acidification, where a known amount of an acid solution is added to a specified amount of product;
- addition of a predetermined amount of an appropriate acid to individual containers during production. Liquid acids are generally more effective than solid or pelleted acids;
- addition of acid foods to low-acid foods in controlled proportions to conform to specific formulations.

The choice of method will depend on the food (Example 5.4).

### **Example 5.4** Cold preservation of pickles by acids

Pickles were traditionally fermented, but more commonly are prepared from fresh by adding a weak organic acid, usually acetic acid, which has an excellent biocidal action. The amount of acid in the equilibrated product is a critical control point and should be measured analytically. This is usually expressed as % acetic acid content. Other acids may be used, but the required levels are higher than those for acetic acid.

A Preservation Index (PI) is calculated from the acid content:

$$PI = \frac{[\text{acidity expressed as acetic acid} \times 100]}{[100 - \text{total solids}]}$$

For products with a PI value above 3.6%, very little or no heat treatment may be needed. However, a food with a  $PI < 3.6\%$  requires some heat treatment; generally a process to achieve in excess of 10 to 15 min at  $75^{\circ}\text{C}$  in the coldest slowest heating spot.

## 5.6 PROCESSING ACIDIFIED FOODS

The heat treatment necessary to achieve commercial sterility of an acidified food is significantly less than that necessary for processing low acid foods, because the acidity of the final product will prevent bacterial spore outgrowth. The heat treatment is only required to kill the less heat resistant moulds, yeasts, vegetative cells of bacteria, to inactivate enzymes, and cook the product where necessary. The heat treatment together with the acidification of the product, are therefore incontrovertible critical factors within an HACCP plan. According to Codex Alimentarius (1993), when establishing a thermal process, the items listed below must be considered:

- pH of the product;
- time to reach equilibrium pH;
- product composition/formulation (including dimensions of solid ingredients);
- levels and types of preservatives;
- water activity;
- microbial flora (including *C. botulinum* and spoilage microorganisms);
- container size and type;
- organoleptic quality;
- product code or recipe identification.

As with acid foods, properly acidified foods only need to undergo a pasteurisation procedure, which targets spoilage microorganisms. During processing of acid foods, often a general rule of achieving  $85^{\circ}\text{C}$  at the coldest spot in the container is used.

However, equilibration of the pH throughout all components of the food can take place during processing, so a hold time is necessary to enable equilibrium. It is therefore often better to calculate a lethality value ( $F$ ) for the appropriate spoilage microorganisms. The time and temperature of each scheduled process is dependent on the equilibrated product pH, as listed in Table 5.3 (see Examples 5.5 and 5.6).



**Table 5.3** Table of suggested F-values for high acid and acidified products.

pH	F-value (minutes) $T_{ref} = 200^{\circ}\text{F}$ ( $93.3^{\circ}\text{C}$ ), $z = 16^{\circ}\text{F}$ ( $8.9^{\circ}\text{C}$ )
< 3.9	0.1
3.9–4.1	1.0
4.1–4.2	2.5
4.2–4.3	5.0
4.3–4.4	10.0
4.4–4.5	20.0

**Example 5.5** Spaghetti in Tomato Sauce

Spaghetti (pasta) in Tomato Sauce is a popular canned food that is made to many different recipes. The amount of pasta (carbohydrate) plays an important role in the amount of heat that the product needs to produce a commercially sterile canned food. The pH of cooked pasta is between 5.6 to 6.1, whereas the pH of the tomato sauce usually varies from 3.9 to 4.6. Thus the sauce recipe and the amount of carbohydrate will determine the final equilibrated pH. Studies have shown that the amount of carbohydrate, irrespective of the pH, also has an effect on the survival of microorganisms (Sognefest *et al.*, 1948). Table 5.4 is used as a guide for the selection of sterilising values.

**Example 5.6** Fresh packed whole pepper pickles (Downing, 1996)

Jalepeno, sweet cherry and hot cherry peppers are packed in a similar way to fresh pack dill pickles. The fresh peppers are blanched in hot water (~70–80°C) for 3–6 min. They are packed into jars, which are then filled with hot brine, containing approximately 5% acetic acid and 9% salt. The jars are then capped and pasteurised to achieve 70–80°C at the coldest spot in the container. The jars are cooled with cold water. Preservatives, like sodium benzoate, may be added to extend the shelf-life of the product once the jar has been opened. Calcium chloride (0.2%) may be added to the brine to help the peppers retain their texture (calcium in the brine replaces calcium lost in the cell wall, which helps it retain its structure).

## 5.7 DESIGN OF PASTEURISATION PROCESSES

The pasteurisation process must be sufficient to eliminate the microorganisms of concern so that they are either destroyed or cannot grow in the final product. It is important to consider the heat resistance of the microorganisms that are of concern to the particular product for which the process is being designed. There are many factors that can influence the survival of microorganisms in different recipe products (Campden BRI, 1992, 2006):

- *Low moisture*: In semi-moist foods the heat resistance of microorganisms is generally increased, similar to in dry environments.
- *Fat*: Generally the presence of high fat content increases the heat resistance of microorganisms due to the protective action of fat and the reduced moisture environment.
- *Water activity*: At reduced water activity levels the heat resistance of microorganisms is generally increased, probably due to the dry conditions. It must also be noted that the type of humectant used to reduce the water activity may result in a different D-value when compared to the same product with the same water activity, but achieved via a different humectant.
- *Salt or sugar levels*: Generally the heat resistance of microorganisms will be increased as the sugar or salt levels increase, again due to the drying effect.
- *pH*: Generally the heat resistance of microorganisms will be reduced at lower pH. Table 5.4 takes this into account when suggested levels of pasteurisation. The recommendations in the following sub-sections were taken from the Campden BRI Guidelines (1992, 2006), as were the data in Table 5.5.

**Table 5.4** Table of proposed process values (F-value) in relation to pH and carbohydrate content of canned foods (taken from Sognefest *et al.*, 1948).

pH of product before heating	Percentage carbohydrate in canned vegetable products		
	3–6%	9–12%	> 15%
4.5 to 5.0	0.5	1.0	2.0
5.0 to 6.0	3.0	4.5	6.0
6.0 and above	4.0	6.0	8.0

**Table 5.5** Table of limiting pH values below pH 4.5 for growth of microorganisms (taken from Campden BRI, 1992).

Organism	Minimum pH for growth	Menstrum
<i>Bacillus licheniformis</i>	4.2	Tomato puree
<i>Clostridium butyricum</i>	4.0	Canned mung beans
<i>B. polymyxa</i>	3.8–4.0	Sucrose nutrient broth
<i>B. macerans</i>	3.8–4.0	Sucrose nutrient broth
<i>C. pasteurianum</i>	3.8 ( $a_w$ 0.98–0.99)	Canned pears
	3.8 ( $a_w$ 0.975)	Mango
<i>B. coagulans</i>	3.85	Tomato juice
<i>C. barati</i>	3.7	Canned mung beans
<i>Lactobacillus brevis</i>	3.5	Citrus fruit
<i>Aspergillus</i> spp.	2.0	Laboratory media
<i>Fusarium</i> spp.	2.0	Laboratory media
<i>Penicillium</i> spp.	2.0	Laboratory media

### 5.7.1 Medium acid range: pH 4.2–4.5

A lowered pH value will inhibit some microorganisms. However, in this pH group there is the risk of outgrowth and spoilage from acid-tolerant heat resistant spore-forming bacteria (e.g. *Bacillus* and *Clostridium* spp.), namely *B. macerans*, *B. polymyxa*, *B. thermoacidurans*, *C. tyrobutyricum*, *C. butyricum* and *C. pasteurianum*.

### 5.7.2 Acid range: pH 3.8–4.2

Heat resistance is closely related to pH; i.e. microorganisms are less heat resistant at lower pH values. The main spoilage organisms in this pH category are *C. pasteurianum*, *C. butyricum* and *C. tyrobutyricum*, as well as some of the acid-tolerant aerobic spore-forming bacteria such as *B. macerans* and *B. polymyxa*.

### 5.7.3 High acid range: pH below 3.8

The major risk in this category is from acid-tolerant microorganisms such as lactic acid bacteria, yeasts and moulds, some of which can produce relatively heat resistant ascospores (e.g. *Byssoschlamys fulva* and *Byssoschlamys nivea*). There is also a risk of spoilage from thermotolerant aciduric spore-forming bacteria (e.g. *Alicyclobacillus* spp.), although this organism will not grow in all foods.

A 6-fold reduction in the microbiological load is generally used when recommending processes for acidified foods. This is lower than the 12-fold recommendations used with low acid foods. The

consensus is that the lower log reductions are for two reasons: first, the processes are based on spoilage organisms and not the lethal toxin producing *C. botulinum* and second, there is a preservation hurdle of acidity present in the foods. The process calculations using D-value and log reductions are the same as for acid and high acid foods, which are discussed in Chapter 4.

Some further processing guidelines (in addition to those in Table 5.4) for products with normal contamination loading are as follows (NFPA, 1968; Campden BRI, 1992):

- For products with pH between 4.3 and 4.6 (e.g. tomato based products), the process should be equivalent to 10 min at 93.3°C (200°F).
- For products with pH between 4.0 and 4.3, the process should be equivalent to 5 min at 93.3°C (200°F).
- For products with pH 3.7–4.2, the slowest heating spot in the container should achieve 85°C (185°F) for at least 5 min or 95°C (203°F) for 30 s.
- For products with pH < 3.7, the slowest heating spot in the container should achieve a minimum of 65°C (149°F) for 16.7 min or 70°C (158°F) for 2.1 min.

## **5.8 CRITICAL CONTROL POINTS IN THE PRODUCTION OF ACIDIFIED FOODS**

A critical control point is a step in the process, which must be controlled to assure food safety. This is discussed in greater detail in Chapter 14.

### **5.8.1 Ingredients**

Fresh vegetables and meat are highly perishable and good quality ingredients must be ensured. This includes receiving good quality ingredients, and handling them in a hygienic fashion with adequate temperature and time controls. Ingredients such as herbs and spices are generally microbiologically stable because of their low water activity, but can harbour high loads of bacterial spores.

The size of the particulates in the formulation must be carefully controlled, because this will significantly affect the time taken to reach an equilibrium pH in the final product. Materials such as peppers, tomatoes and cucumbers may need to be sliced, chopped (to specific sizes) or pierced to provide intimate contact with the acidified brine.



**Fig. 5.3** Pickled onions.

### 5.8.2 Heat processing

An adequate thermal process must be delivered to ensure that the final product is commercially sterile. A process with a minimum of a 6-log reduction of the appropriate microorganism must be used, and the appropriate temperature must be achieved for the particular container size, shape and fill weight. This temperature must be held for the appropriate time in a retort or a hot fill at the appropriate fill temperature and hold time should be used for products not subjected to a post packaging heat treatment (Fig. 5.3).

### 5.8.3 Post process equilibrated pH

Extreme care must be taken when acidifying low acid foods so that they can be minimally processed without concerns over low acid regions. The time taken for the pH of the product to equilibrate must be sufficiently short so that no microorganisms have time to grow and produce toxin or cause spoilage.

The UK Department of Health Guideline (1994) states that pH equilibration of the product at pH 4.5 or below should take place within 4 hours of the end of the heat process. This guideline also advises that final equilibration of pH is not always achieved in this

time, is not easily controlled, and may vary with different ingredients. However, it must be measured within a fixed time and suggests 24 hours from the end of the heat process.

The USA FDA (21CFR 114.3) regulations for acidified low acid foods states that the equilibrated pH of the product must be 4.6 or below by the end of heat processing. The low acid components in a product must be less than 4.6 within a period of 48 hours. A finished equilibrium pH of 4.6 or below to prevent botulism is always a critical control point for acidified foods. The pH of the brine or sauce must be sufficiently acid to result in an equilibrated pH that is less than or equal to 4.6. The critical control point for acidified foods is a finished equilibrium pH of 4.6 reached within 24 hours.

#### **5.8.4 Container integrity**

Container closures (caps, seals or double seams) should be intact and free from food product on sealing surfaces in order to provide a proper hermetic seal. This should remain hermetic through the product shelf-life.

#### **5.8.5 pH during product shelf-life**

The pH of the product should be monitored during the shelf-life. Any increase in pH could indicate microbiological activity, or improper equilibration, with the risk of microorganisms growing. These are measurements that should be carried out by the processing company.

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## 6 Heat Preserved Chilled Foods

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Ready meals and prepared foods have seen fast growth, as consumers spend less time preparing meals in the home. One growth sector in Europe is refrigerated products of extended durability in which foods are given an in-pack retort process to extend their chilled shelf-life beyond 10 days. These are heat preserved foods stored in chilled conditions, and are sometime known as REPFEDS (refrigerated products of extended durability). Since the name is ungainly, references to REPFEDS will be kept to a minimum.

Also of importance are the short shelf-life foods that include ready-to-eat cooked meat, fish and poultry products. The severity of the heat process given to a product depends on the length of chilled storage and must be sufficient to target the organisms that can grow over the storage time. Food products with up to 10 days chilled shelf-life are, currently in the UK, required to receive a pasteurisation treatment at least equivalent to 2 minutes at 70°C (DoH, 1989). These products include cooked poultry, meat as an ingredient for chilled foods, ready meals, plus a wide range of pies and pastries, and soups and sauces for the high quality end of the market. Microorganisms of concern with this group of foods are the aerobic pathogens; this includes *Listeria monocytogenes*, *Salmonella* spp. and *Escherichia coli*. These organisms exist only as vegetative cells and as such are relatively easy to kill by heat.

As shelf-life is extended beyond 10 days, the possibility exists that psychrotrophic strains of *Clostridium botulinum* can grow. *Sous-vide* was one of the first technologies to take shelf-life beyond 10 days. It originated in France as a mild thermal process (e.g. 70°C for 40 minutes) for the manufacture of high quality foods sold to the catering sectors (Campden BRI, 1992a). More recent *sous-vide* processes have targeted the psychrotrophic strains of *C. botulinum* that have required the process severity to be increased beyond 70°C



for 40 minutes. A process equivalent to 10 minutes at 90°C is designed to achieve at least 6-log reductions in numbers of *C. botulinum* spores (FSA, 2008).

Changing lifestyles have ensured that consumer preferences continue to increase for chilled prepared foods. Many forms of thermal processing can be used for their production, and the choice of method depends on the final product quality and its intended shelf-life. This chapter looks at three main types:

- (i) pasteurising all components separately and packing the product either hot or cold;
- (ii) in-pack pasteurising the product;
- (iii) packing cooked protein with raw vegetable in high care environments.

In-pack pasteurisation in combination with chilled storage is being achieved through optimisation of existing retort-based equipment and thermal processing regimes, which can be used to produce ready meals of high quality. This is one of the major growth sectors for the UK (and European) food industry. Recent developments in overpressure retorts and packaging formats have allowed this ready-meal sector to advance at a rapid rate. Retorting has the advantage of pasteurising both the ready meal and packaging together, which can extend the shelf-life under chilled storage considerably above 10 days.

## **6.1 UNDERSTANDING MICROORGANISM BEHAVIOUR**

In order to understand how thermal processing is used to manufacture a heat preserved chilled food it is important to know how microorganisms behave. This is best understood by adopting the HACCP approach. The HACCP context quantifies three main areas of biological risk, and these are:

- (i) introduction to the food;
- (ii) growth within that food;
- (iii) survival through the production stages.

A factory HACCP plan will consider introduction, growth and survival at all stages of manufacture (Mortimore and Emond, 2008) and put in place critical control points (CCPs) for their

control. Temperature is the main preservation action, both from the storage of raw materials and finished products, but also from the processing perspective.

There are categories of temperature sensitivity of microorganisms that help to define the growth behaviour of microorganisms and also relate to the required severity of the thermal process. These were introduced in Chapters 1 to 5 but are outlined again here for their relevance to heat preserved chilled foods. Microorganisms are divided into the following categories according to their growth patterns at various temperatures. The first three categories are of greatest importance in chilled foods manufacture.

- Psychrophilic (cold loving), with growth temperature of 12–20°C.
- Psychrotrophic (cold tolerant), with growth temperature of 20–30°C.
- Mesophilic (medium range), with growth temperature between 30 and 45°C.
- Thermophilic (heat loving), with growth temperature between 45 and 65°C.
- Thermoduric (heat enduring), which can survive above 65°C, but cannot reproduce at these temperatures.

Most of the pathogenic microorganisms fall within the mesophilic category, such as *Salmonella* spp., *L. monocytogenes* (LM) and *E. coli* O157, and so food production conditions are designed to minimise their growth and survival during manufacture. Note that LM tends towards psychrotrophic growth characteristics but is more typically mesophilic. These tendencies for organisms to grow or survive towards the limits of the above categories illustrate that these categories only provide a convenient set of divisions. Microorganisms have the ability to evolve within their short lifecycle stages, so can adapt to adverse conditions. Over a period of weeks or months it is possible for a factory strain of a microorganism, for example *Listeria*, to evolve and develop some resistance to dilute cleaning chemicals or the ability to multiply several degrees colder than its preferred growth range. This presents a challenge to chilled food factories and requires good standards of hygiene coupled with temperature control, otherwise microorganism colonies can evolve and become established.

It is also important to understand the four stages in bacterial growth, of which the first two, namely the lag phase and log phase, are most important during chilled food manufacture:

- (i) *Lag Phase*: during which the bacteria acclimatise to their environment, which can be several hours long.
- (ii) *Log Phase*: during which reproduction occurs logarithmically for the first few hours, where conditions for growth are ideal, and it is during this period that most toxin production starts.
- (iii) *Stationary Phase*: during which the bacteria's reproduction rate is cancelled by the death rate.
- (iv) *Mortality or Decline Phase*: during which exhausted nutrient levels or the level of toxic metabolites in the environment prevents reproduction, with the result that the bacteria gradually die off.

The lag phase is critical in chilled foods production because it allows the food manufacturer to complete the processing and assembly stages for a food without microorganisms germinating from spores or increasing in cell numbers. A chilled food manufacturer will usually prepare the food in a clean environment held at low temperatures (8–10°C) to control and suppress growth. Preparation is usually done in a low care environment where standards of hygiene are high but do not need to be at the levels required with high care environments. The latter are essential when foods are assembled without any further process, for example a thermal process step, being given to the foods.

Thermal processing conditions of hold temperature and hold time are calculated from knowledge of the intended storage conditions, which dictate which microorganisms can grow. This is a form of commercial sterility, although many thermal processing specialists do not recognise the definition when applied to the chilled foods sector.

### **6.1.1 Pathogenic microorganisms relevant to chilled foods**

There are effectively two categories of chilled foods in which a heat process is applied to extend the workable shelf-life:

- (i) Food products sold chilled with up to 10 days shelf-life are currently, in the UK, required to receive a pasteurisation treatment at least equivalent to 2 minutes at 70°C (DoH, 1989). These products include cooked poultry, meat as an ingredient for ready meals, some ready meals, plus a wide range of pies, pastries, soups and sauces for the high quality end of the market. Microorganisms of concern with this

- group of foods are referred to as aerobic pathogens, which include *L. monocytogenes*, *Salmonella* spp. and *E. coli* (Campden BRI, 1992b). These organisms exist only as vegetative cells and as such are relatively easy to kill by heat.
- (ii) As shelf-life is extended beyond 10 days, the possibility exists that psychrotrophic strains of *C. botulinum* can grow. *Sous-vide* was one of the first technologies to take shelf-life beyond 10 days, which originated in France as a mild thermal process (e.g. 70°C for 40 minutes) for the manufacture of high quality foods for catering sectors (Campden BRI, 1992a). More recent *sous-vide* processes have targeted the psychrotrophic strains of *C. botulinum* (e.g. 90°C for 10 minutes), with the result that the required process severity needs to be increased. A process equivalent to 10 minutes at 90°C is designed to achieve at least a 6-log reduction in numbers of *C. botulinum* spores (Campden BRI, 1992b; FSA, 2008). The precise shelf-life will depend on spoilage organisms in the raw materials.

A common theme with pasteurisation treatments is the design of a 6-log kill process. For example, if the initial loading of psychrotrophic *C. botulinum* spores is  $10^2/\text{g}$  in an unprocessed food, then a 6-log process will reduce this to  $10^{-4}/\text{g}$  in the processed food. This is a very small number of surviving cells, which is best described as a probability of a spore surviving the process rather than an absolute number. In this case, the probability is 1 spore in 10 000 g of food.

The following section provides more information on two of the main pathogenic microorganisms of relevance to extended life chilled foods. The first, *C. botulinum*, is the target organism for the 10 minutes at 90°C process, and the second, *Bacillus cereus*, will become important as shelf-lives are extended upwards of around 30 days.

#### 6.1.1.1 *Clostridium botulinum*

*C. botulinum* is a ubiquitous bacterium which is found in soil, fresh water and in the gastrointestinal tract of animals and fish (Marth, 1998). There are seven types of *C. botulinum* (A to G) separated by the properties of the toxin; of these seven toxin types, A, B and E are known to cause human disease, and type F has occasionally been implicated. Type E is often associated with fish and aquatic environments (ACMSF, 1992). As well as

**Table 6.1** Heat resistance of psychrotrophic *C. botulinum*.

Psychrotrophic strain	Heating substrate	Temp (°C)	D value (minutes)	z value (°C)	Reference
<i>C. botulinum</i> type B	Cod	90	1.10	9	Gaze and Brown, 1991
<i>C. botulinum</i> type E	Tuna in oil	82.2	6.6	6.1	Bohrer <i>et al.</i> 1973
<i>C. botulinum</i> type F	Crab meat	82.2	1.16	6.38	Lynt <i>et al.</i> 1979
<i>C. botulinum</i> type B	Crab meat	94.4	2.9	8.5	Peterson <i>et al.</i> 1997
<i>C. botulinum</i> type B	Phosphate buffer with added lysozyme	90	18.1	7.6	Peck <i>et al.</i> 1993
<i>C. botulinum</i> type E	Phosphate buffer with added lysozyme	90	12.6	8.3	Peck <i>et al.</i> 1993
<i>C. botulinum</i>		90	1.5		ECFF, 1996

different toxin types, *C. botulinum* is also classed into groups, with groups I and II responsible for the largest number of food-borne botulism cases. Spores of group I are proteolytic and have a higher heat resistance; typically these spores are controlled by an  $F_03$  process (described in Chapter 3). Organisms in group I are not of concern to chilled foods, as the minimum growth temperature is 10 to 12°C (Peck, 2006). Group II organisms are non-proteolytic and have a lower minimum growth temperature of 2.5 to 3.0°C and therefore are of concern in the chilled food sector (Peck, 2006).

The occurrence of *C. botulinum* in raw foods is varied and may be dependent upon geography, for example, in Europe high levels are reported in fish from Scandinavia (Lindström, 1996). Non-proteolytic *C. botulinum* outbreaks are associated most frequently with processed fish (Peck, 2006). The heat resistance of the different types of *C. botulinum* are given in Table 6.1, which shows that these values can vary depending on the type and the substrate used for heating. Foods containing lysozyme and recovery medium with added lysozyme have been shown to increase the heat resistance of non-proteolytic *C. botulinum* (Peck *et al.*, 1993). This issue has stimulated many debates amongst thermal microbiologists.

The heat resistance values accepted as the target values for the 10 minutes at 90°C process are those of Gaze and Brown (1991). Worked example 6.1 presents how the process was derived.

### Worked example 6.1 6-log process for psychrotrophic *C. botulinum*

Measured  $D_{90}$  value of 1.1 min.

Target 6 log reductions in psychrotrophic *C. botulinum*

The equation to calculate the target F-value is:

$$F = D_T \cdot \log \left( \frac{N_0}{N} \right)$$

Hence, the target F-value is  $6 \times 1.1 = 6.6$  min. This was rounded up to 10 min, which was a decision taken by the ACMSF committee (ACMSF, 1992), and so the actual log reductions of psychrotrophic *C. botulinum* spores achieved by 10 min at 90°C is just greater than 9.

#### 6.1.1.2 *Bacillus cereus*

*B. cereus* is a ubiquitous spore-forming bacterium, which is found in soil and many foods such as rice, milk, dairy products, spices and vegetables, and therefore can be present in cooked chilled foods (Guinebretiere *et al.*, 2003). The organism can cause two different types of food poisoning; emetic and diarrhoeal, depending on the type of enterotoxin produced (ACMSF, 1992). In the emetic form of poisoning, symptoms are nausea and vomiting and this is often associated with rice dishes (Altayar and Sutherland, 2006). Generally this organism causes food poisoning at levels of  $10^5$  to  $10^8$  cells per g in the contaminated food, but has caused limited outbreaks at levels of  $10^3$  to  $10^4$  per g (EFSA, 2005).

Some strains of the organism are psychrotrophic and are capable of growth at 4°C, which makes them of concern for refrigerated pasteurised foods (Choma *et al.*, 2000). This organism can display high levels of heat resistance, as shown in Table 6.2, often higher than those used to establish the current process recommendations (see above for *C. botulinum*). Therefore, the risks of food poisoning are controlled by selection and/or treatment of raw ingredients and a reduction in shelf-life. For example, if a particular ingredient, such as a dried spice, has a high level of *Bacillus* spp., this ingredient can be heat treated before being added to the recipe dish.

Psychrotrophic strains of *C. botulinum* and *B. cereus* are the two organisms that could result in food poisoning incidents with

**Table 6.2** Heat resistance of *B. cereus* spores.

Organism	Heating substrate	Temp (°C)	D value (minutes)	z value (°C)	Reference
<i>B. cereus</i> (emetic and diarrhoeal strains)	Buffer, pH 7	85	32.1–106 (mean 45.4)	6.9–13.9 (mean 8.9)	Johnson <i>et al.</i> (1982)
<i>B. cereus</i> spores psychrotrophic strain	Trypticase soy broth, pH 6.0	90	5.0–7.1	–	Membre <i>et al.</i> (2006)
<i>B. cereus</i>	Buffer, pH 7.0	90	71	9.8	Goepfert <i>et al.</i> (1972)
<i>B. cereus</i>	Buffer, pH 7.0	100	8.0	10.5	Molin and Smygg (1967)
<i>B. cereus</i> vegetative cells	Phosphate buffer	90	0.33–0.50	–	Kamat <i>et al.</i> (1989)
<i>B. cereus</i> spores	Phosphate buffer	90	8–15	–	Kamat <i>et al.</i> (1989)
<i>B. cereus</i>	Buffer, pH 7	85	220	9.8	Goepfert <i>et al.</i> (1972)
<i>B. cereus</i> spores, psychrotrophic strains	Sterile distilled water	90	< 1.5	–	Choma <i>et al.</i> (2000)
<i>B. cereus</i> spores, unable to grow at ≤10°C	Sterile distilled water	90	0.9–5.9	–	Choma <i>et al.</i> (2000)
<i>B. cereus</i> spores, isolated from Spanish rice	Sterile distilled water	90	3.23–23.26	–	Sarrías <i>et al.</i> (2002)
<i>B. cereus</i> spores, two strains	Honey	105	1.7–2.1	–	Etoa and Adegoke (1996)

extended shelf-life foods. Most other known pathogens either cannot grow at chilled conditions or are less heat resistant.

### 6.1.2 Microorganisms likely to be found in chilled foods

Apart from food poisoning risks, there is a commercial requirement to manufacture food products that retain their appeal to consumers throughout the duration of shelf-life. It is therefore important that the relevant food spoilage organisms are also taken into account when establishing the thermal process. Spoilage organisms are key to shelf-life determination and are sometimes ignored because their effects on the food are to cause it to spoil but not to produce toxins. However, the number of types of spoilage organism is substantially greater than for pathogenic organisms.

**Table 6.3** Levels of microorganisms in the raw ingredients of a prawn makhani curry (cfu/g).

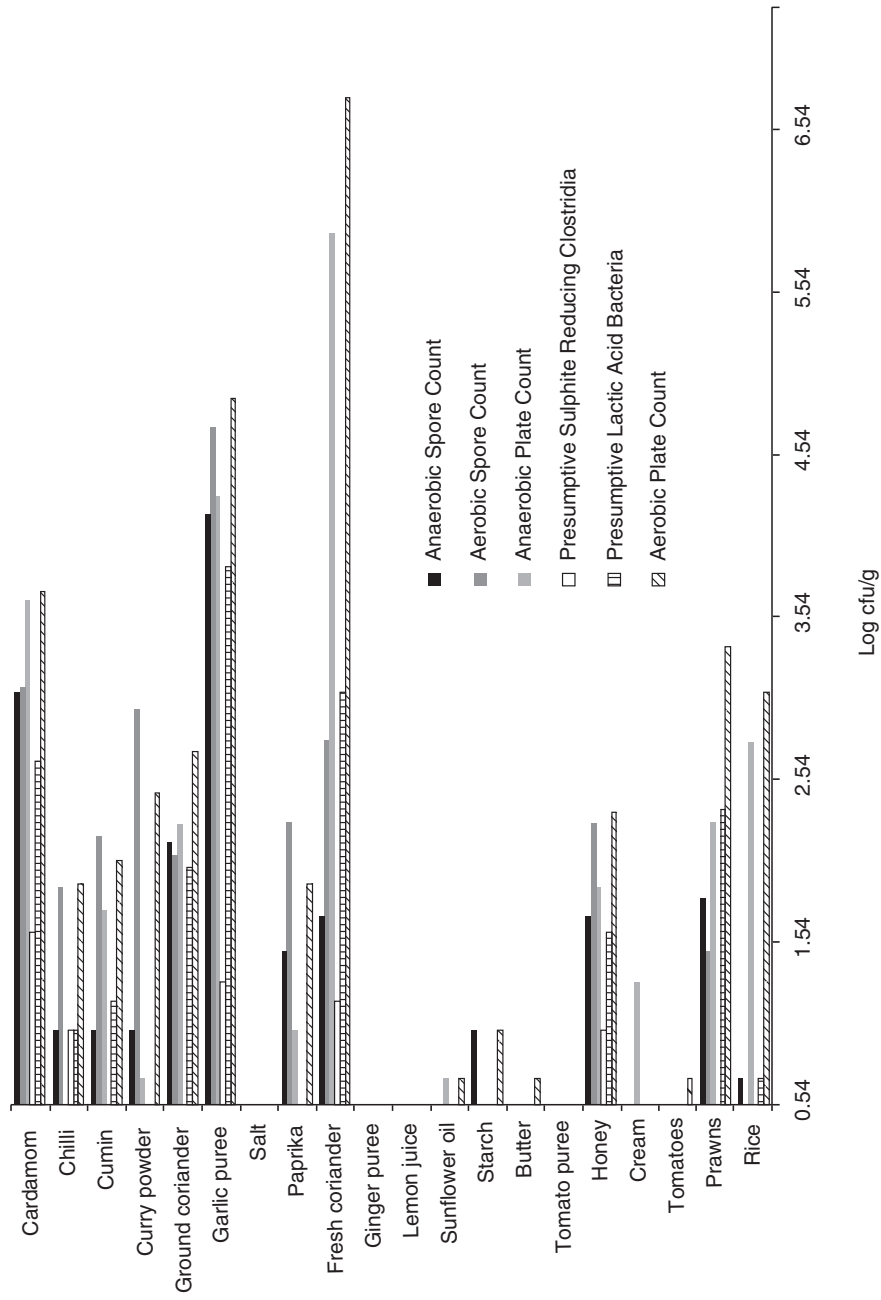
Ingredient	APC	Lactics	PSRC	ANPC	ASC	ANSC
Rice	1.20E+03	5.00E+00	<5	5.90E+02	<5	5.00E+00
Prawns	2.30E+03	2.27E+02	<5	1.90E+02	3.00E+01	6.50E+01
Tomatoes	5.00E+00	<5	<5	<5	<5	<5
Cream	<5	<5	<5	2.00E+01	<5	<5
Honey	2.18E+02	4.00E+01	1.00E+01	7.50E+01	1.85E+02	5.00E+01
Tomato puree	<5	<5	<5	<5	<5	<5
Butter	5.00E+00	<5	<5	<5	<5	<5
Starch	1.00E+01	<5	<5	<5	<5	1.00E+01
Sunflower oil	5.00E+00	<5	<5	5.00E+00	<5	<5
Lemon juice	<5	<5	<5	<5	<5	<5
Ginger puree	<5	<5	<5	<5	<5	<5
Fresh Coriander	5.50E+06	1.20E+03	1.50E+01	9.80E+05	6.00E+02	5.00E+01
Paprika	8.00E+01	<5	<5	1.00E+01	1.90E+02	3.00E+01
Salt	<5	<5	<5	<5	<5	<5
Garlic puree	7.80E+04	7.00E+03	2.00E+01	1.90E+04	5.10E+04	1.50E+04
Ground Coriander	5.09E+02	1.00E+02	<5	1.81E+02	1.20E+02	1.40E+02
Curry powder	2.91E+02	<5	<5	5.00E+00	9.65E+02	1.00E+01
Cumin	1.10E+02	1.50E+01	<5	5.50E+01	1.60E+02	1.00E+01
Chilli	8.00E+01	1.00E+01	1.00E+01	<5	7.50E+01	1.00E+01
Cardamom	5.10E+03	4.45E+02	4.00E+01	4.50E+03	1.30E+03	1.20E+03

One recent piece of work by Tucker *et al.* (2008) used a fish curry ready meal as an example product in which the microorganisms in each raw material were enumerated. The curry was a prawn makhani, chosen because it contained many of the raw materials known as those that can introduce high microbial loading to food recipes. Microbiological tests included:

- *APC*: aerobic plate count;
- *Lactics*: lactic acid bacteria;
- *PSRC*: presumptive sulphite reducing Clostridia;
- *ANPC*: anaerobic plate count;
- *ASC*: aerobic spore count;
- *ANSC*: anaerobic spore count.

Results from the microbiological tests on the raw ingredients showed high levels in the fresh coriander with levels of  $5.5 \times 10^6$  and  $9.8 \times 10^5$  cfu/g for the APC and ANPC, respectively (Table 6.3). In general, the herbs and spices contributed a high proportion of the microbiological loading for this product. These data are also shown graphically in Fig. 6.1.





**Fig. 6.1** Levels of microorganisms in the raw ingredients of a prawn makhani curry (cfu/g). For a colour version of this figure, please see the colour plate section.

Results in Table 6.3 and Fig. 6.1 demonstrate that many of the herbs and spices in recipe dishes contain high numbers of micro-organisms. Levels of spoilage organisms were considerably higher than for pathogenic organisms, with the latter being isolated by the ANPC and ANSC tests. Spores of psychrotrophic *C. botulinum* (ANSC) were only found in appreciable numbers in the spices, with garlic puree and cardamom having the highest levels (15 000 and 1200 cfu/g, respectively). When diluted into the curry recipe as a small percentage of the total, the spore numbers in the product prior to the thermal process are low. This gives confidence in the 6-log recommendation for establishing a 10 minutes at 90°C process. However, it does require that preparation conditions for a recipe dish are controlled to maintain these low numbers, otherwise the chances of surviving *C. botulinum* spores increases.

## 6.2 METHODS OF MANUFACTURE

Production methods for chilled foods are many and varied, but can be categorised into those where the thermal process step occurs: (a) prior to packaging, for example, using heat exchangers and ovens; or (b) after packaging, for example, in a retort. Applying the thermal process before packaging offers most variety in terms of production methods, and it is common for factories making short shelf-life meals to be divided into high and low care (or risk) areas. Equipment for achieving the thermal processing step for both in-pack and in-line systems is described in more detail in Chapter 7.

Packaging materials for heat preserved chilled foods do not need to provide the strength or protection demanded by fully sterilised ambient stable foods. There are several reasons for this:

- temperatures are in the pasteurisation region (e.g. 70–105°C) rather than sterilisation (e.g. 112–132°C);
- pressure differential between inside and outside of the package is much lower;
- storage life is a few weeks compared with many months;
- storage temperature is 5 to 8°C and so gas transfer occurs at slower rates.

Hence, the packaging is typically in barrier plastics, either pouches, bowls or trays, but with some paperboard cartons used for

### **Box 6.1** Food poisoning example: Canned chilled carrot juice

In the USA in 2006/7, Bolthouse Farms manufactured a chilled carrot juice in a metal can, and this initiated four separate *C. botulinum* poisoning incidents over a few months. The product was intended for storage in the refrigerator but was mistakenly put into store cupboards because it was similar in appearance to other ambient stored cans.

In September 2006, three people living in Georgia developed food-borne botulism that was traced to the carrot juice from a single can. Soon after, there was an additional case in Florida and two more in separate incidents in Ontario, Canada. At least one person died and two remain on ventilators today.

In June 2007, the FDA modified its guidance for refrigerated low-acid juices to recommend adding a validated juice-treatment method, such as acidification or appropriate thermal treatment, to decrease the risk of *C. botulinum* contamination, should any breaches in refrigeration occur. No further incidents are reported for this or other products (FDA, 2007).

soups. Multi-layered materials are required to provide barrier protection against ingress of water, oxygen and light. Details on the package construction and properties are not appropriate for this book and can be found in *Food Packaging Technology* by Coles *et al.* (2003). These multi-layered packages are less strong than the metal can and require greater caution during the processing steps to avoid container damage. This is particularly important for retorted foods in which retort overpressure is required to maintain the container shape during the process. This is considered in one of the following sections.

One very important consideration when choosing the packaging materials is to avoid metal cans for chilled foods. These should not be used for this type of food because of the risks of the consumer confusing how the cans should be stored. This is highlighted in the recent botulism outbreaks in the example in Box 6.1.

## **6.2.1 Thermal process step applied prior to packaging**

This is the method for chilled food manufacture that was used when the industry sector first gained popularity soon after refrigeration was available to households. The first food products were

relatively simple in their construction, with most being commodity items such as milk and fruit juice. During the 1980s, the UK was instrumental in pioneering a more ambitious chilled foods market in which the concepts of convenience food were started. Foods such as soups, sauces and ready meals were often prepared in large kettles and hot filled into packages. These were then chilled or frozen in the sealed packages using air blast refrigeration. The heat process in the kettles is adequate to knock out aerobic pathogens in the food by achieving 2 minutes at 70°C. Heat from hot filling provides a surface pasteurisation effect, although at the time unquantified, and this is sufficient to control yeast and mould on the packaging surfaces. Chilled food prepared in this way has a shelf-life of up to 10 days.

A significant reliance is placed on the chilled storage because of the lack of quantification of the time and temperature processes achieved in both cooking and hot filling. Within the 10-day shelf-life there is scope for the thermal process to be applied inadequately but without the implications for food safety that arise with ambient stable foods. This is because there is unlikely to be enough time for the psychrotrophic microorganisms to grow in the chilled conditions. Microorganisms, for example LM, are known to grow down to temperatures close to 0°C but this is in ideal laboratory conditions and the growth rates are very low. Therefore, this process is reliable and only tends to fail if the chilled storage is broken.

Methods to validate the pasteurisation achieved during cooking and filling have developed in recent years. These are described in Chapter 9.

When companies demand longer shelf-life it is necessary to increase the thermal process severity for the cooking process and to ensure the hot filling achieves at the very minimum a yeast and mould process. The driving force is the retailer's desires to reduce waste on its premises and provide the consumer with more days of useable shelf-life in the fridge. The FSA advice (FSA, 2008) for the extended process is to achieve 10 minutes at 90°C during cooking ( $T_{ref}$  90°C,  $z$  9°C), so that 6-log reductions in psychrotrophic strains of *C. botulinum* are achieved. This organism can grow down to low temperatures (e.g. 3–8°C), albeit slowly, but over a shelf-life that can be upwards of 30 days, the chances of it growing need to be considered.

One option used by some companies to increase the security of the packed food is to hot fill into the package. Evidence from commercial products that are hot and cold filled suggests that hot filling provides a few more days of shelf-life. Hot filling needs to take place in clean conditions so that bacterial contamination is

prevented and the risks are only from air-borne yeast and mould spores. These are easier to kill by heat. The hot fill process should achieve at least 2 minutes at 70°C on the packaging surfaces ( $T_{\text{ref}}$  70°C,  $z$  7.5°C). Contamination from bacterial spores is likely to survive the hot filling process and so attention to filler cleaning and start-up procedures, and filler room hygiene is essential.

Filling after processing incurs a higher risk than when processing a filled and closed container. Factories that manufacture REPFEDs will usually enclose the filling environment in a high care or high risk area (Campden BRI, 1992a). Standards of hygiene are stricter than in a low care environment where the food product receives its cooking process. If microbiological contamination gets into a food before or during cooking, the thermal process will destroy the contaminating microorganisms. This assurance is not present during filling. The next section outlines some of the practices involved in assembling product within high care environments.

#### 6.2.1.1 *Low care–high care factories*

Ready meals of high quality are being manufactured in Europe using cooked protein (e.g. chicken, meat or fish) and raw vegetable components. These are usually separated in different compartments of the package. The thermal processing steps take place in a low care environment and are followed by packing into the sealed final package in a high care environment. Strict control of hygiene in the high care area is essential in order that microorganisms are not introduced to the food. Once packaged, there is no further preservation hurdle apart from chilled storage.

It is increasingly common for the cooked protein to be transported frozen from countries in which manufacturing costs are lower than in Europe, for example, Thailand, Brazil and China. The minimum process for cooked protein is to achieve at least 2 minutes at 70°C at the core ( $T_{\text{ref}}$  70°C,  $z$  7.5°C). Although this is not a traditional thermal process, there is still a need to validate the heat treatment and to control its implementation in a factory using HACCP approaches. Methods for validating these processes often require techniques such as microbiological or biochemical TTIs, because of the continuous cooking and cooling equipment that is used. Chapter 9 provides details of these techniques.

The advantage of the assembly method for high quality prepared meals is in the quality of protein and vegetable that can be achieved. Vegetables such as lettuce cannot be cooked without complete loss in texture, while others such as peppers and spring onions easily lose their texture. By assembling a meal with all components

chilled to 5 to 8°C and maintaining the chilled shelf-life for only a few days, it is possible to produce textures that cannot be achieved by thermal processing alone.

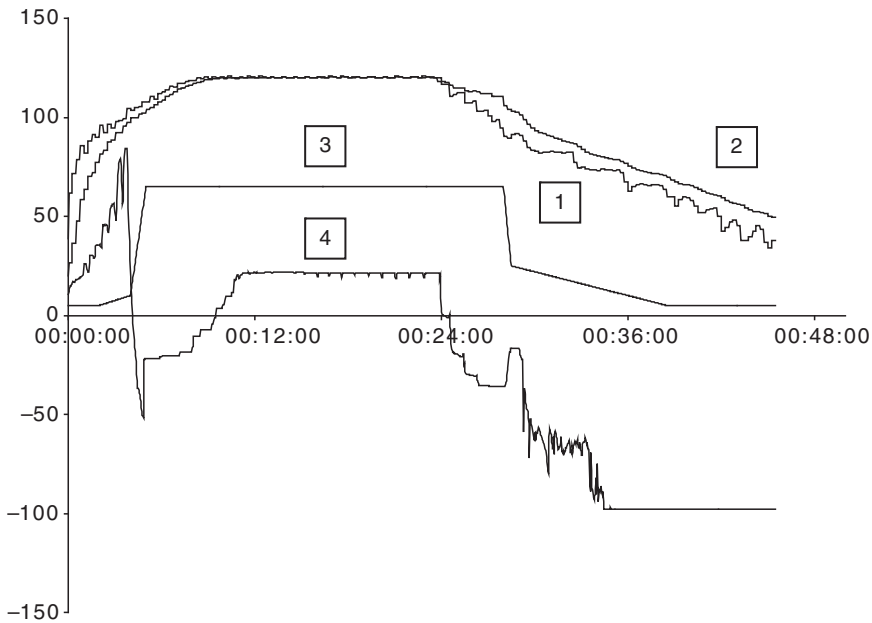
This method of chilled food manufacture is more complicated than the few paragraphs above suggest. It uses modified and controlled atmospheres to suppress microorganism growth, applies new technologies such as pulsed light and other surface treatments, and places emphasis on hurdles to microbial growth. It is debatable whether it should be included in a book on thermal processing, but for completeness and because of the cooked protein components, it is included. Tucker (2008) gives further information on the above techniques in his book on *Food Biodeterioration and Preservation*.

### 6.2.2 Thermal process step applied after packaging

Retorting after filling is now the preferred method for extending the shelf-life of heat preserved chilled foods. It is more secure than hot filling because the retort process pasteurises both the packaging and the food. Ready meals have benefited from this to the extent that the majority of UK chilled ready meals (in trays) are now manufactured by retorting the filled package. The shelf-life can go considerably beyond 10 days, although there is no recommendation on how many days are achievable. This decision is the responsibility of the manufacturer.

The retorting process is carried out in a similar way to that for canned foods; however, the difference is in the need to operate the process using an overpressure that counteracts expansion of the packages. If the food is a ready meal in a plastic tray, the tray will be made from flexible plastics (e.g. polypropylene or CPET) and the lid will be a very thin film (e.g. polyester). These trays are delicate and distort easily at small pressure differentials. One of the first retort manufacturers to seize on this opportunity was the French company Lagarde in partnership with the UK company Holmach Ltd. They engineered the steam/air retorting system with air overpressure so that it could be applied to processing delicate plastic trays. Many of the early heat preserved chilled food products on UK retailer shelves were thermally processed in Lagarde steam/air retorts.

Processing a delicate plastic tray requires a higher level of retort control than with a stronger metal can. The main control issue is to maintain an overpressure in the retort that is just sufficient to force the tray back to its original size and shape. Figure 6.2 illustrates the changes in pack deflection that occur during processing, as measured using a deflection sensor positioned with the sensing tip just touching the upper pack surface. In this example the

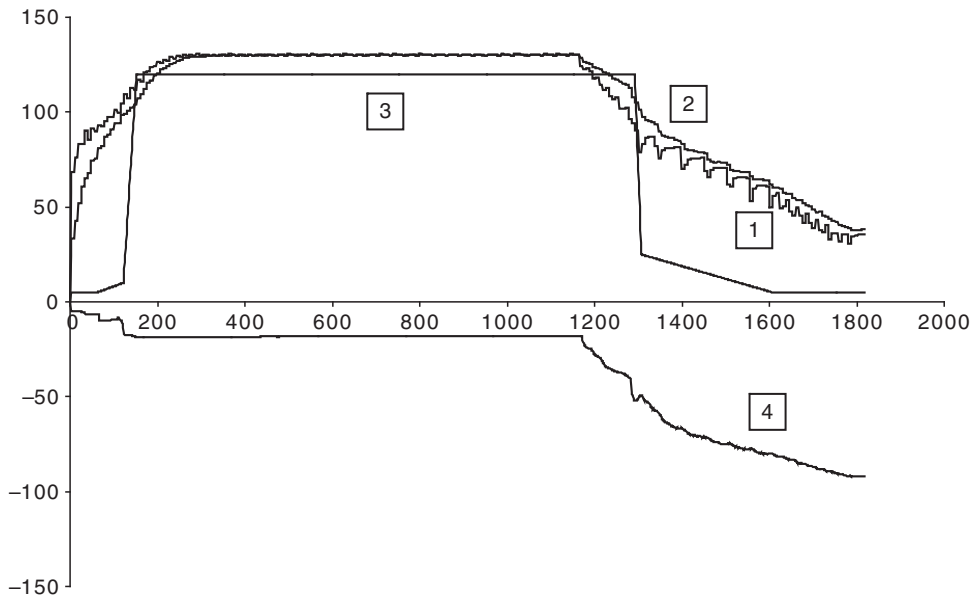


**Fig. 6.2** Graph showing changes in deflection in the upper surface of a flexible package processed in an overpressure retort (1 – retort temperature, 2 – product temperature, 3 – retort pressure, 4 – deflection sensor reading).

package was a ready meal tray, the retort used steam/air, and the food product was water. Figure 6.2 shows the tray increase in volume during the venting period of the retort, with the deflection brought under control at the end of the vent period by increasing the retort pressure to counteract the expansion. Overpressure was held steady during the hold period and for further time into cooling while the product was hot and internal pack pressure was high. The example in Fig. 6.2 is not an ideal deflection curve but it illustrates how deflection changes during the retorting cycle.

Further complications can arise because of differences in air content or pressure inside the filled packs, which can create inconsistency in pack deflection across a retort load. This effect is exacerbated with changes in fill temperature, for products filled hot (for viscosity purposes) in which the cooked batches cool during the time taken to fill the packs for a retort load. The first packs filled are at a higher temperature and so they draw a higher vacuum level inside the packs as the product cools compared with the cooler packs filled at the end of the batch. Fill temperature differences may only be 20°C, but this is sufficient to generate pressure differences across the retort load.

Figure 6.3 illustrates improved pack deflection control by reducing the air headspace and increasing the retort overpressure.



**Fig. 6.3** Graph showing changes in deflection in the upper surface of a flexible package processed in an overpressure retort; with lower headspace and high retort pressure than for Fig. 6.2 (1 – retort temperature, 2 – product temperature, 3 – retort pressure, 4 – deflection sensor reading).

Less gas and more overpressure forces the tray lid closer to its original position. This avoids the damaging changes in lid deflection that are detrimental to pack integrity.

#### 6.2.2.1 *Caution with latent heat for frozen protein*

As with ready-meal assembly in high care environments, retorted foods are also now using cooked protein imported in frozen form. This is economic, easier to handle than fresh protein, can be stored for long periods, and does not suffer from protein cook-out that damages the appearance and texture of sauces. However, there is one major disadvantage of using frozen protein in a retorted ready meal, and this is the issue of the latent heat of freezing that has to be overcome before the product temperature can rise from 0°C.

Latent heat is an energy intensive property that occurs as water and dissolved substances (e.g. salts, acids, colours) change their state from liquid to solid. To reverse this process, as is required in retorting a ready meal containing frozen protein, the same high quantities of energy are required. Worked example 6.2 demonstrates the proportion of energy required with frozen protein.



### Worked example 6.2 Energy required to thaw frozen chicken

The ready meal is a 400 g chicken curry with 150 g of chicken. The retorting process raises the meal temperature from 0 to 90°C. Assume the frozen protein (150 g) is at 0°C and the sauce (250 g) is also at 0°C but is not frozen.

The energy required to thaw the frozen chicken is given by:

$$Q = m \cdot L$$

where  $Q$  is the energy required (J),  $m$  is the mass of frozen chicken (kg) and  $L$  is the latent heat for frozen chicken (assume a value for water) at  $33.5 \times 10^4 \text{ J} \cdot \text{kg}^{-1}$ :

$$Q = 0.15 \times 33.5 \times 10^4 = 50250 \text{ J}$$

So 50250 J are required to thaw the chicken, with the chicken temperature remaining at 0°C.

The energy required to raise the temperature of the chicken and sauce is given by:

$$Q = m \cdot C_p \cdot \Delta T$$

where  $Q$  is the energy required, known as sensible heat (J),  $m$  is the mass of chicken or sauce (kg), and  $C_p$  is the specific heat capacity for chicken or sauce (assume a value for water) at  $4186 \text{ J kg}^{-1} \cdot \text{K}^{-1}$ :

$$Q = 0.4 \times 4186 \times 90 = 150696 \text{ J}$$

So 150696 J are required to raise the thawed chicken and sauce from 0 to 90°C.

The total energy to process the ready meal (excluding packaging) is the sum of both the latent and sensible heat components, which is 200946 J.

Latent heat is 25% of the total energy; which is a significant amount.

The worked example of a ready meal with 30 to 40% frozen protein is commonly experienced with this industry. Companies with canning backgrounds are aware of the issues with frozen ingredients. Guidance is available to use defrosted materials or restrict the proportion to a low level (e.g. 5–10%) that will defrost before the can enters the retort (Campden BRI, 1977; IFTPS,

1995). The implications of a lengthy defrosting period on establishing a safe process makes heat penetration testing difficult. Of particular difficulty is how to ensure the worst case heating condition is one of the limited number of experimental trials carried out. This is a challenge that is currently facing the industry. The solution may be in the experimental methods for achieving the worst case heating pack or in the way process calculations are applied to the data.

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## 7 Processing Systems

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This chapter explains the various processing systems that can be used for manufacturing heat preserved foods. For convenience they are divided into in-pack and in-line systems, which are often known as retorts and continuous systems. We do not go into the detail of each commercial system, of which there are many, but describe the operating principles.

The main types of batch retort are described, for example steam, steam-air, water immersion, raining and sprayed water. Also included are the in-pack continuous retorts such as hydrostatic and reel & spiral cooker-cooler systems.

In-line systems include heat exchangers and pressure vessels. Examples include heat exchangers based on plates, tubes or scraped surfaces, plus some of the interesting adaptations of these basic designs. Food products are heated (pasteurised or sterilised) prior to filling into the package, which can either be an aseptic fill for ambient shelf-life or a clean fill for chilled shelf-life. Aseptic filling is considered to be outside of the scope of this book.

The final section looks at some of the more commercially relevant newer technologies, such as ohmic and microwave processing, that can deliver heat treatments either in-pack or in-line.

### 7.1 IN-PACK PROCESSING: RETORT SYSTEMS

In the traditional in-pack process, the packs are filled and hermetically sealed before being thermally processed in a retort. Care must be taken to ensure that the heat penetrates to the slowest heating point in the can, so that no part of the food is left under-processed. A metal can is the ideal package from a processor's perspective because, relative to other packaging media, it offers

high production speeds, pack size flexibility, and high compression strength to withstand physical abuse during processing and distribution. However, many of the recent retorts have arisen because of the desire to process more sensitive pack types. After heating, the food needs to be cooled, and it is vital that no post-process contamination occurs through the package seals or seams.

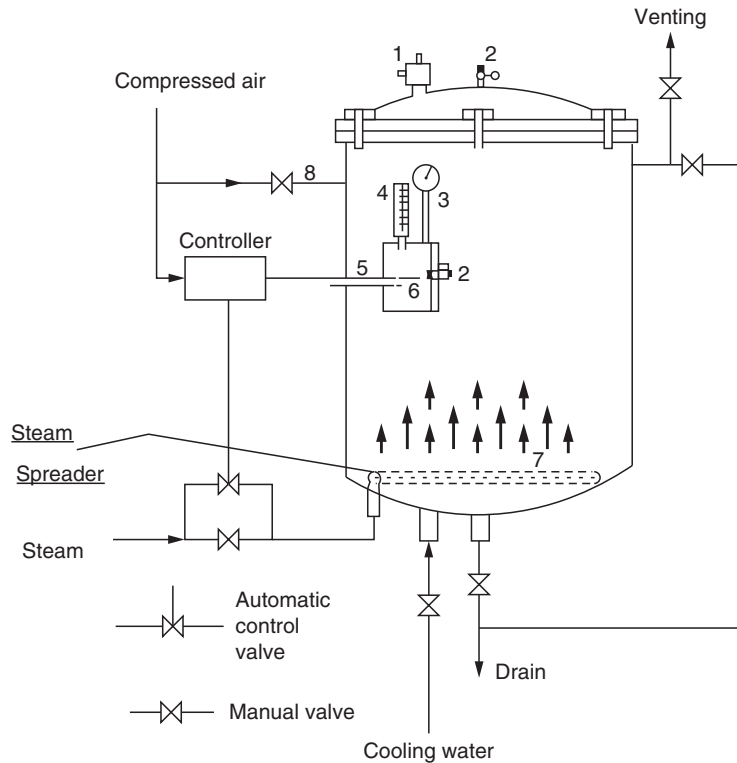
Batch retorts (Fig. 7.1) operate with a variety of heating media, which includes condensing steam, mixtures of steam and air, water immersion, or water droplets either sprayed or rained onto the packs (May, 2000; Britt, 2008). These offer considerable flexibility for many combinations of food type and package. By applying an air overpressure, above that of the saturated steam pressure, the package shape can be maintained through the process so that stress on the seals is reduced. This allows delicate packages such as pouches and trays to be processed, for glass jars it prevents the lids from being forced off, and it ensures that plastic packs retain their shape and size.

The baskets (or crates) within a batch retort can be rotated in order to induce mixing inside the food by end-over-end agitation of the packs. This increases the rate of heat transfer to the thermal centre (i.e. slowest heating point) of the pack. Typical rotation speeds can vary between 2 and 30 rpm, depending on the strength of the pack and the convective nature of the food inside the pack. For example, a plastic pouch containing rice would be rotated slowly (e.g. 2–5 rpm) so that the delicate pack and its contents are not damaged, however, the rotation is sufficient to reduce the process times to an extent that economic gains are made and measurable quality benefits are achieved.

### 7.1.1 Condensing steam retorts

Steam retorts are historically the method of choice for processing foods packaged in metal cans (Fig. 7.1). They were the system used when the canning industry was established over 100 years ago. These retorts are vented at start-up to eliminate air pockets in the retort that can result in low temperature regions and reduced heat transfer. Very high surface heat transfer coefficients associated with the condensing steam process ensure uniform heating throughout the vessel.

Nowadays, most companies in Europe and the USA have replaced their steam retorts with a retort type that can apply an overpressure. This enables a wider variety of container types to be processed.



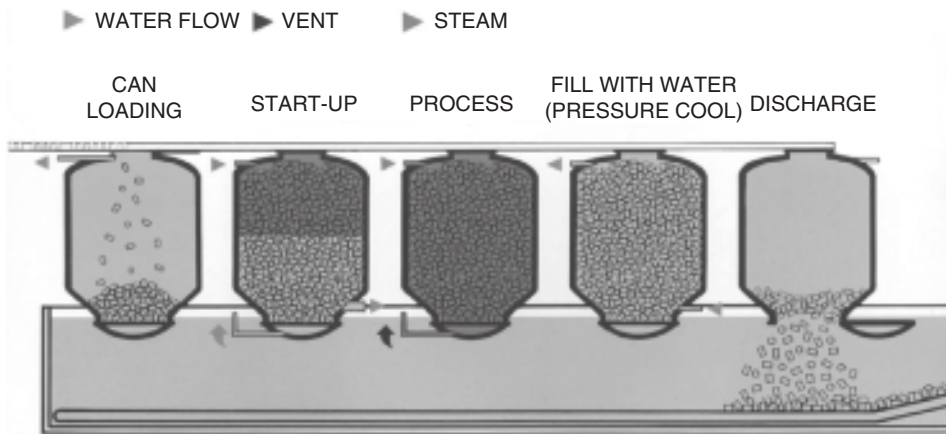
**Fig. 7.1** Batch condensing steam retort.

### 7.1.2 Crateless retorts

These consist of a single can conveyor and a bank of batch processing vessels (Fig. 7.2) that are arranged so the flow of filled cans is almost continuous. At the start of an individual process, the retort is initially filled with water to cushion the cans as they enter the retort directly from the conveyor. When an individual retort is full, as determined by a can counter, the conveyor diverts the continuous flow of cans to the next retort in the bank. Simultaneously, the door is closed on the filled retort, a bottom vent is opened, and steam enters the vessel through a circular distribution spreader at the top of the retort, rapidly evacuating the remaining cushion water together with any air present in the retort. Cans are then heated in condensing steam for the design process time. At the end of heating, the retort is flooded with cooling water, and the product is pressure cooled for a specified length of time. At the end of the pressure cooling step, a door located in the bottom of the vessel is opened, and cans are discharged onto a conveyor located in a cooling canal. The processed cans move through the cooling canal and then on to the labelling area.



## TYPICAL PROCESSING SEQUENCE



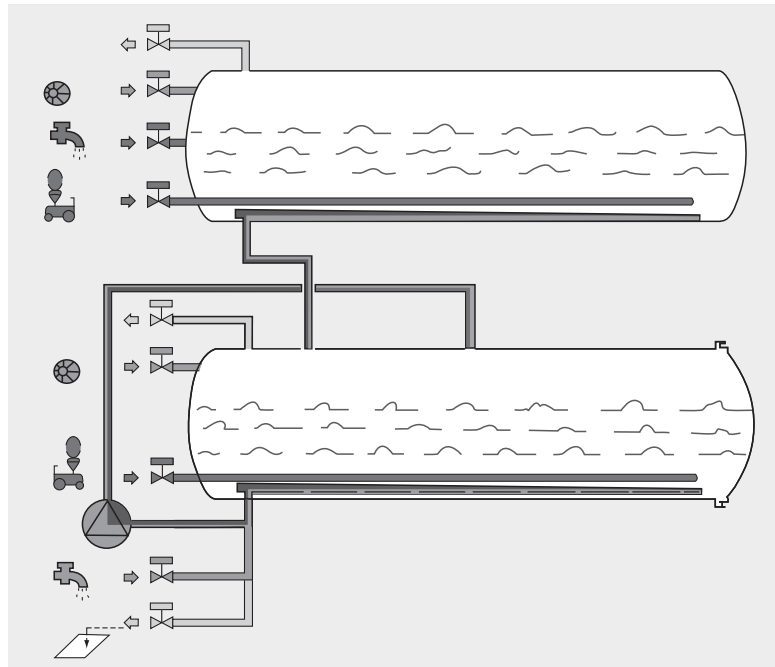
**Fig. 7.2** Crateless retort showing the sequence in operating a bank of retorts.

The concept is an interesting one but with some drawbacks. On the positive side, energy efficiency is improved over the traditional steam retort by eliminating the need for a venting time. Also, the flow of cans through a bank of crateless retorts can be almost continuous, and therefore is efficient. However, the method of filling the retorts by dropping cans into water is known to lead to a small level of can damage. Orientation of the cans in a crateless retort is totally random, as the falling cans settle into a random packing pattern. This results in cans being processed in different orientations and nesting of shallow profile cans, which reduces the heat penetration effectiveness.

Most crateless retorting systems have been removed over the last 20 years and replaced with modern overpressure retorts. The following section describes some of the most important designs for overpressure retorts.

### 7.1.3 Water immersion retorts

One of the first types of water immersion retort was the Stock Rotomat (now Satori Stocktec GmbH, Germany), as shown in Fig. 7.3. During a retort cycle, processing water is preheated in the upper vessel and then released at the start of the process to fill the processing or lower vessel. This reduces the come-up time that would otherwise be lengthy in heating a large volume of water to processing temperature. When the containers are fully immersed, water is pumped from the base of the lower vessel through an



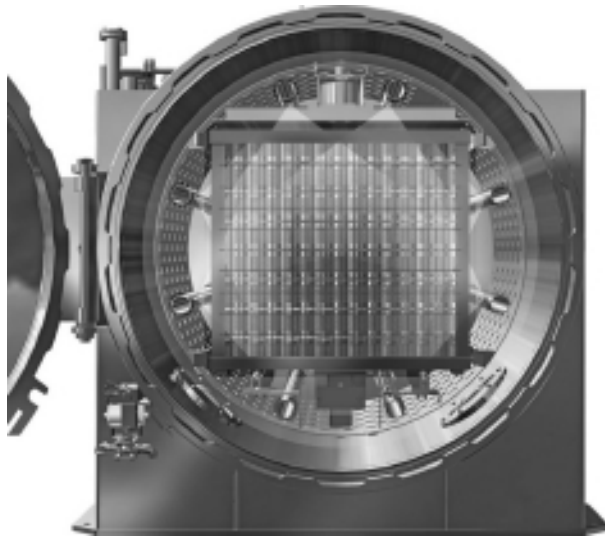
**Fig. 7.3** Water immersion retort showing the two vessels (courtesy of Holmach Ltd).

external steam injection heat exchanger and back into the top of the same vessel. At the end of the hold period, cold water is injected into the top of the processing vessel while hot water is pumped from the base of the processing vessel back into the upper vessel to be reheated and used in the next cycle. Overpressure is established by introducing steam or compressed air to the retort during processing.

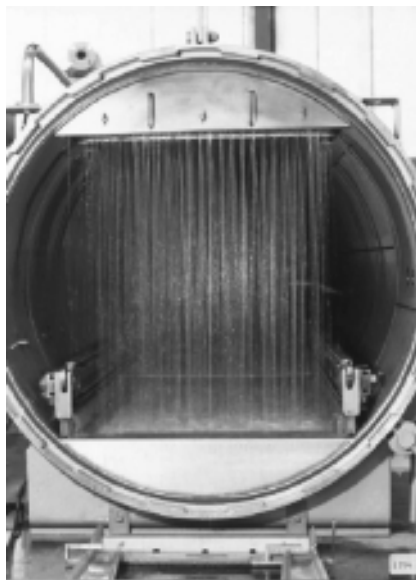
The major disadvantage of the water immersion system is the need to operate with two vessels, which makes this system considerably more expensive than the alternatives. As a result, their popularity has gone down over the last 15 years. One distinct advantage of immersion is the buoyancy provided by the water that allows glass jars to be processed using quite high end-over-end rotation speeds (e.g. up to 20rpm). This can result in high quality sauce products where product movement is used to increase heat penetration rates.

#### 7.1.4 Water spray and cascade

These retorts operate by circulating water from the base of the retort through an external heat exchanger and then distributing it inside the retort, either through spray nozzles (Fig. 7.4) or as a



**Fig. 7.4** SuperAgi TM concept for a water spray retort (courtesy of JBT FoodTech, formerly known as FMC FoodTech).



**Fig. 7.5** Water cascade retort showing the powerful water shower.

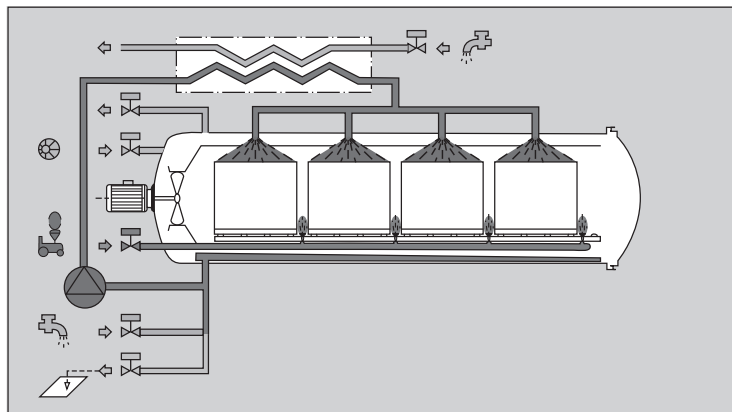
cascade generated by flow through a perforated plate (Fig. 7.5). The resulting spray or cascade of heated water is then directed through the load to heat individual containers. Overpressure is established by introducing steam or compressed air to the retort during processing. Several designs are in commercial use.

Barriquand (now Steriflow SAS) pioneered the Steriflow system, in which a perforated plate provides a powerful cascade of droplets over the containers. This system has been used for cylindrical metal cans and allows cans with easy-open ends to be processed by operating with an overpressure towards the end of the heating phase. Heating and cooling of the process water uses a tubular heat exchanger. Several incidents of canned food spoilage are known to have resulted from leaks in the heat exchanger that allowed untreated cooling water to contaminate the sterilised process water. This is one point of weakness of this system. Another is the introduction of top-up water into the retort during cooling. Most of the older retorts have since been modified to prevent cooling water being introduced during cooling.

FMC (now JBT FoodTech) developed the Sundry sprayed water system that uses a series of spray nozzles to direct water into the crates of food containers. This is a recently introduced retort but has quickly gained popularity because of its flexibility and excellent temperature distribution. The latest version has a ring of spray nozzles that rotates (SuperAgi retort) around the food containers so that the temperature distribution is improved further.

### 7.1.5 Steam/air retorts

These retorts utilise condensing steam to supply the heat energy for heating and compressed air for overpressure (Fig. 7.6). Processes start with a short vent cycle to provide a large initial flow of steam into the retort and to vent out most of the air. After venting, steam and air are added independently to obtain the desired operating conditions. A high-speed circulation fan pulls



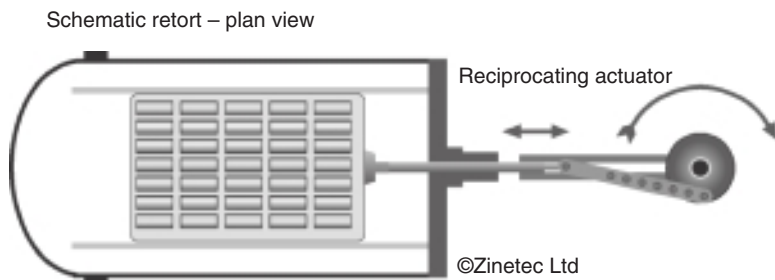
**Fig. 7.6** Steam/air retort (courtesy of Holmach Ltd).

the steam/air mixture through the load and then forces it to the back along the length of the retort, either through an annular space between the rotating cage and the retort shell, or through side plenum chambers in a static system.

At the end of the hold period, the cooling cycle commences with a pre-cool when cooling water is sprayed slowly into the circulating steam/air mixture to collapse the steam in a controlled manner. Air is also added to maintain the retort pressure and ensure package integrity. After the pre-cool, the circulation fan is stopped and water accumulated in the base of the retort is pumped through an external heat exchanger to cool the water. The circulation pump returns the cooled water back into the processing vessel via a row of spray nozzles at the top of the retort. In rotary processes, rotation commences with steam-on and continues through the completion of the cooling cycle. With no buoyancy forces to protect the containers from damage, rotation speeds are limited to a maximum of around 15 rpm.

### 7.1.6 Shaka retorts

This is a unique concept and a recent addition to the options with batch retorts. Its point of difference is that it uses high frequency longitudinal agitation instead of end-over-end or axial rotation. This is the mode of agitation that an individual would use if asked to agitate a cylindrical metal can of food product. The principle is that the headspace will be forced through the liquid or semi-solid food during one lateral agitation cycle. Reductions in process time are claimed to be significant, which are highlighted by heating factors ( $f_h$  values) that drop from 30 to 40 minutes in a static process to 2 to 3 minutes in a Shaka process (for a standard can, 73 × 115 mm). This has benefits in reducing energy use and process times, and in doing so increasing production efficiency. Figure 7.7 shows the Shaka retort principle.



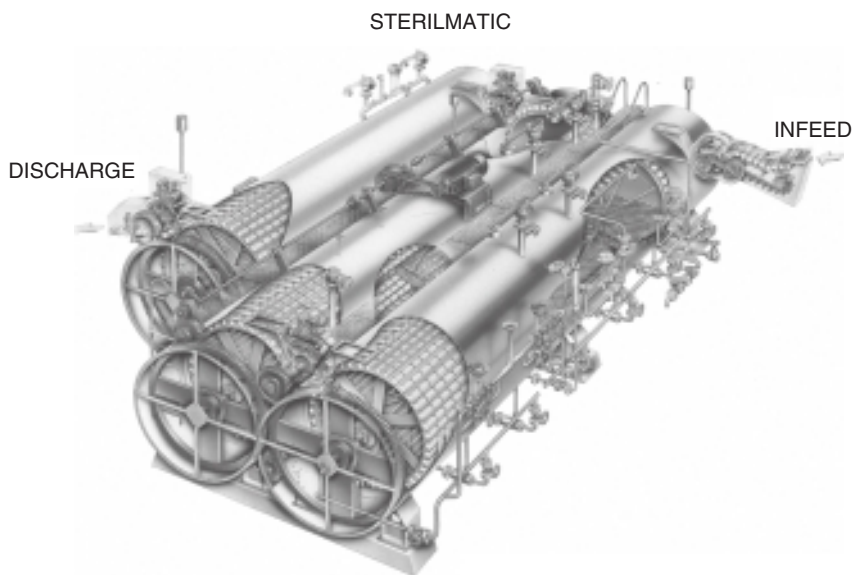
**Fig. 7.7** Shaka retort principle showing the reciprocating basket movement.

All the above retorts operate in a batch mode in which the containers are loaded into crates that are loaded into the retort. A more efficient means of operating a sterilisation process is to continuously load the system. Continuous retorting systems come in two main types: reel & spiral and hydrostatic. Both uses the ability of the metal can to roll along a pathway as the means of propelling the cans into the system.

### 7.1.7 Reel & spiral retorts

In these systems, cans enter and exit the processing vessel through mechanical pressure locks (Fig. 7.8). Once in the vessel, cans move through a spiral track mounted on a reel that is rotating inside a horizontal cylindrical shell. In one revolution of the reel, cans roll by gravity along the bottom part of the arc ( $\sim 90\text{--}120^\circ$ ), which provides most of the product mixing within the can. This is known as fast axial rotation (FAR) and delivers a very rapid rate of heat penetration to the can centre. The cans are essentially static as they pass through the remainder of the arc ( $\sim 240\text{--}270^\circ$ ).

Systems are usually configured as a number of vessels with different functions connected in series. For example, a pre-heat shell, heating shell and cooling shell could make up a complete system. Soups, sauces and foods that can move within the can are processed in reel & spiral cooker-coolers. These will benefit



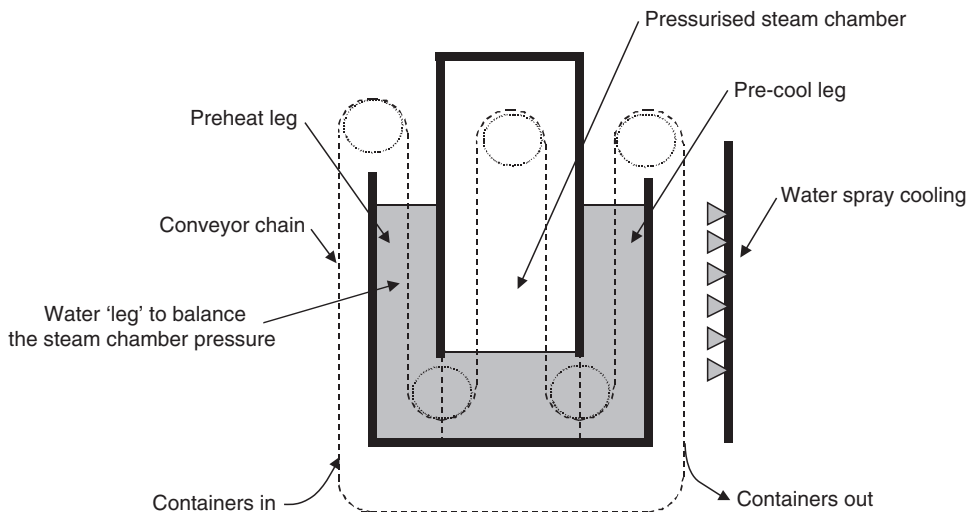
**Fig. 7.8** Reel & spiral retort (courtesy of JBT FoodTech , formerly known as FMC FoodTech).

from agitation. It is estimated that almost 50% of the worldwide production of foods in metal cans is produced using reel & spiral retorts.

### 7.1.8 Hydrostatic retorts

A hydrostatic retort (Fig. 7.9) does not invoke such dramatic rotation but instead carries the cans on carrier bars through various chambers. The only rotations are half-turns as the cans move between the chambers. It uses the pressure generated by the height of water in the entry and exit legs to create a pressure in the heating dome equal to the saturated steam pressure at the processing temperature. During processing, containers undergo a pre-heat treatment as they move through the entry leg, are exposed to condensing steam in the heating dome, are cooled as they move through the exit leg, through a cooling water spray, and are then discharged. Typical chamber temperatures are, for example, pre-heat at 80 to 90°C, sterilisation at 120 to 130°C, pre-cool at 80 to 90°C and final cooling at 40°C.

The length and speed of the conveyor or chain carrying the containers determine the processing time in the steam dome. Because of their large size, venting of these retorts is time and energy intensive. This, combined with a high capital investment, requires that these retorts generally run 24 hours per day, 7 days per week. Hydrostats are used for high viscosity foods where



**Fig. 7.9** Hydrostatic retort showing the movement of cans through different chambers.

rotational forces cannot be utilised to increase heat transfer rates, for example in solid petfoods and meat products.

## 7.2 IN-LINE PROCESSING: HEAT EXCHANGERS

In-line processing of liquid foods, as compared to in-container processing, offers many economic advantages (Tucker and Bolmstedt, 1999; Emond, 2000). It is claimed that by minimising the exposure of food to the adverse effects of high temperatures and long processing times, commercial benefits can be realised in improved product quality, increased safety and increased plant throughput. A classic example of this is with UHT milk, where an in-pack sterilisation process usually results in excessive browning reactions taking place and an undesirable product. By operating an HTST process (high temperature, short time), it is possible to reduce these browning effects and produce milk that has a more acceptable appearance and taste to the consumer (Dairy Processing Handbook, 2003). A heat exchanger such as a plate pack or narrow bore tube will be the core of this process and will deliver a rapid rise and fall in milk temperature. The heat exchanger part of the HTST process for milk is not now a difficult technical challenge, with the exception of minimising the fouling that builds up over the run-time and reduces heat transfer efficiency.

A challenge in the design of heat transfer equipment for the liquid food industry are the so-called prepared food products, such as tomato products, soups and sauces, and dessert products. These products are normally of high viscosity as well as of complex composition. In each case the optimal heat processing equipment has to be chosen in order to retain particulate integrity, flavour and colour of the end-product. There is not one heat exchanger that will process all of these types of products from fibrous fruit juices to soups with particulates. These are the product types for which it is necessary to understand how their flow behaviour interacts with the heat exchanger choices.

A typical continuous processing line consists of preparation modules, the actual heat exchangers and a filling machine. The preparation modules are used mainly for formulated food products, for example, vanilla puddings and salsa sauces, where the product is prepared and exits this section ready to be pasteurised or sterilised. The processing modules comprise the heat exchangers where the product flow is counter-current to the heating or cooling media. Filling systems will either operate hot or cold, or require a



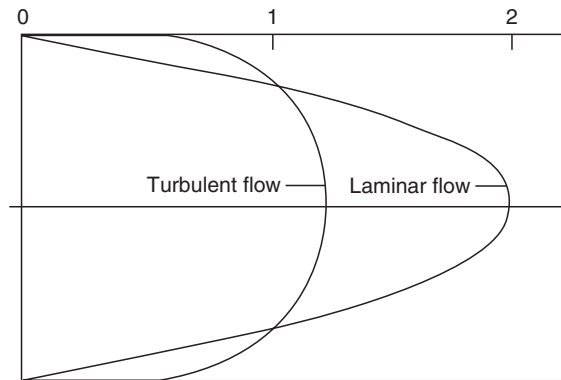
balance tank or aseptic storage tank that acts as the buffer between the processing and filling modules.

With respect to flow behaviour or rheology, most of the formulated products are typically non-Newtonian, showing in many cases quite extraordinary behaviour. Few foods flow as Newtonian liquids, apart from milk and thin fruit juices. Most food products are shear-thinning and some also display time-dependent properties caused by the complex macromolecular structures that are used in their formulation. These properties must be considered when designing a processing system, in order that excessive damage is avoided to the delicate structures. Depending on the rheological properties of the product and the possible presence of particulates, the design and choice of equipment can vary significantly from case to case. Various additives, for example thickeners and stabilisers, often also change the physical and rheological properties of the product. The next section provides a brief introduction to some of the complexities with flow behaviour of foods.

### 7.2.1 Flow behaviour

In the design of heat exchangers and choice of heat exchanger configurations, the flow behaviour of the product has to be taken into consideration (Barnes, 2000). The flow behaviour will affect, for instance, the residence time distribution in the pipework and hence the design of heat exchangers and holding cells to obtain the sufficient thermal treatment. There are two types of flow that will be experienced by a flowing food; these are laminar and turbulent, but with a transitional region between the two types as the flow changes from one to the other. It is important to know which flow regime is present in all parts of a continuous process so the residence times can be calculated correctly.

The basic difference between laminar (streamline) and turbulent flow is well known, as is the effect on the velocity profile from heating or cooling of the product. For example, the maximum velocity in laminar flow, originating from the parabolic velocity profile, is theoretically twice the mean velocity, and in turbulent flow it is around 20% higher than the mean velocity (Fig. 7.10). Laminar flow is assumed to occur up to Reynolds numbers of around 2100, whereas turbulent flow occurs at greater than 10 000 (Equation 7.1). The region in between 2100 and 10 000 is referred to as the transitional region, because the flow regime is changing from laminar to turbulent. This is a region that equipment designers will try to avoid because of the uncertainties in flow behaviour



**Fig. 7.10** Velocity profiles for turbulent and laminar (streamline) flow showing the ratio of maximum velocity to average velocity.

and the key relationship between fastest and mean velocity. Should a heat exchanger be operated under transitional flow, then it would be safe to assume that the fastest liquid along the pipe centre could be travelling twice as fast as the mean velocity. The US FDA takes a Reynolds number of 4000 as the division between laminar and turbulent flow, and assumes there is no transitional region. This is a simplification of what happens in practice, but it does make process calculations much clearer.

For viscous products, the flow conditions are nearly always laminar. A tomato paste steriliser, for instance, operates at Reynolds numbers (Re) around 1 (see Worked example 7.1). For milk and

### Worked example 7.1 Reynolds number for a tomato ketchup

Density =  $1000 \text{ kg m}^{-3}$

Velocity in tube =  $0.8 \text{ m s}^{-1}$

Tube diameter =  $0.075 \text{ m}$

Viscosity =  $760 \text{ cP}$  ( $0.76 \text{ Pa.s}$ )

$$\text{Re} = \frac{0.075 \times 1000 \times 0.8}{0.76} = 78.9$$

Flow conditions are laminar.

Assume maximum centreline velocity is  $2 \times$  the mean velocity in the holding tube.

**Worked example 7.2** Reynolds number for a fruit juiceDensity = 1000 kg m<sup>-3</sup>Velocity in tube = 1.2 m s<sup>-1</sup>

Tube diameter = 0.075 m

Viscosity = 5 cP (0.005 Pa s)

$$\text{Re} = \frac{0.075 \times 1000 \times 1.2}{0.005} = 18\,000$$

Flow conditions are turbulent.

Assume maximum centreline velocity is 1.2 × the mean velocity in the holding tube.

juice products, flow conditions are almost always turbulent (see Worked example 7.2):

$$\text{Re} = \frac{d_h \cdot \rho \cdot v}{\mu} \quad (7.1)$$

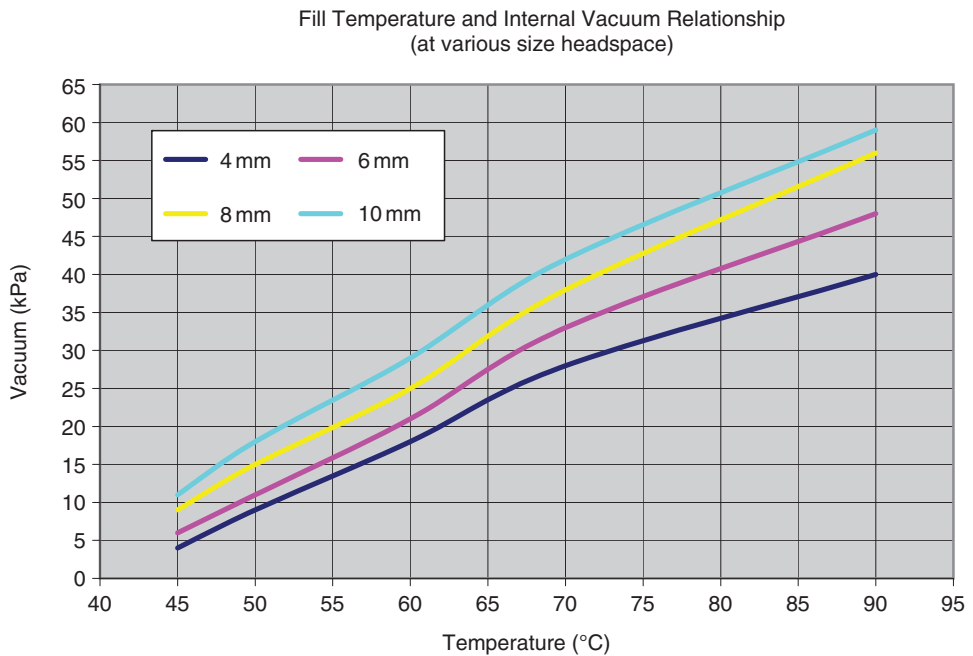
where  $d_h$  is hydraulic diameter of the processing system, m,  $\mu$  is dynamic viscosity of liquid, Pa s,  $\rho$  is density of liquid, kg m<sup>-3</sup> and  $v$  is mean velocity in the processing system, m s<sup>-1</sup>.

Equation 7.1 is for Newtonian liquids that have a viscosity independent of shear rate. Most, if not all, formulated foods contain macromolecular thickening agents in which the viscosity depends on the shear applied in the processing system. These non-Newtonian foods are certain to flow under laminar conditions because of their high viscosity values, and they also display velocity profiles that are still more complex. As the degree of non-Newtonian behaviour increases, the velocity profile increases in flatness across the pipe cross-section. This means in practice that the maximum velocity decreases from its Newtonian value of twice the mean velocity. However, there are few commercial operations that do not apply the factor 2 when calculating holding tube length, irrespective of the measured flow behaviour index.

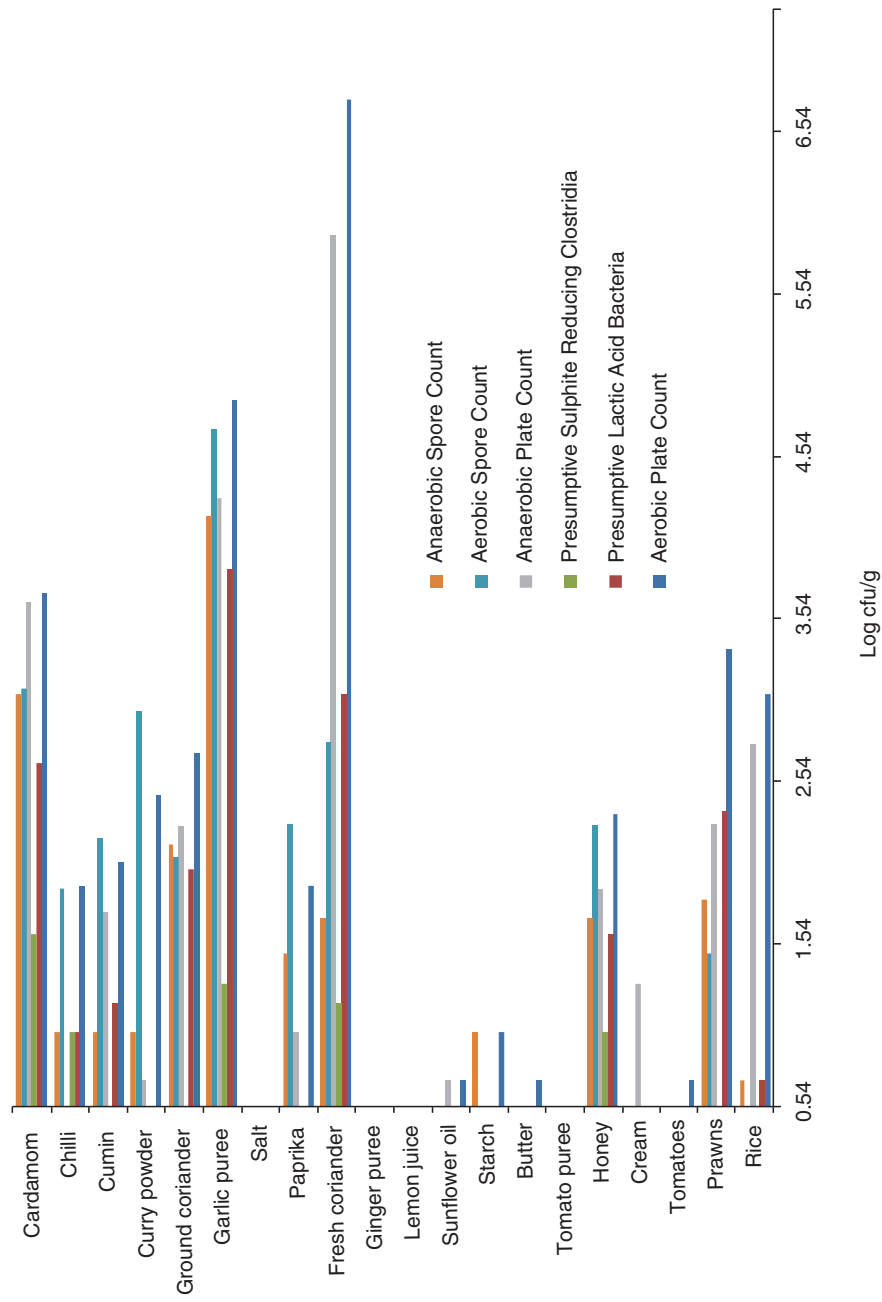
Further complications to the velocity profile arise when additives, for example xanthan or gellan gum, are used. These have viscoelastic properties and are beneficial for enhancing the

pH 0	Battery Acid (30%) $\text{H}_2\text{SO}_4$
pH 1	Gastric Acid (1.1)
pH 2	Cola (2.5)
pH 3	Apricots (3.2)
pH 4	Tomatoes (3.8–4.4)
pH 5	Rain (5.5)
pH 6	Egg Yolk (5.7)
pH 7	Human Blood (7.2)
pH 8	Egg Whites (8.5)
pH 9	Baking Soda (8.5)
pH 10	Milk of Magnesia (10.6)
pH 11	Household Ammonia (11.2)
pH 12	Household Bleach ( $\text{NaClO}$ ) (12.6)
pH 13	Household Lye ( $\text{NaOH}$ ) (13.5)
pH 14	Concentrated Sodium Hydroxide ( $\text{NaOH}$ )

**Plate 1** Materials of varying pH from battery acid at around pH 0 through to strong alkalis at pH 14.



**Plate 3** Relationship between fill temperature and the vacuum formed, for various head-space volumes.



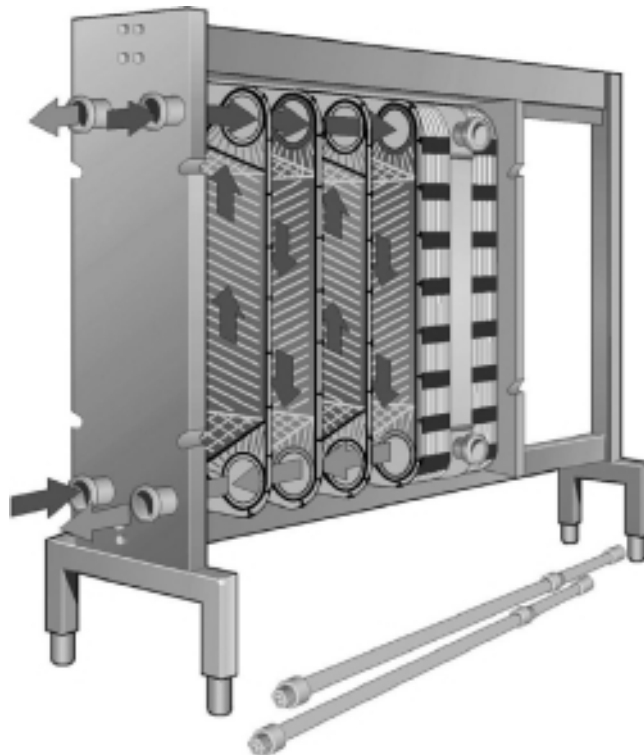
**Plate 2** Levels of microorganisms in the raw ingredients of a prawn makhani curry (cfu/g).

particulate carrying properties of a sauce. The so-called yield value, normally a measure of the product's willingness to flow by itself, for example from a storage tank or bottle of ketchup, is also a measure of the particulate carrying abilities. A significant yield value, typical of paste-like products, also adds to the flatness of the velocity profile and hence further increases the deviation from the parabolic shape.

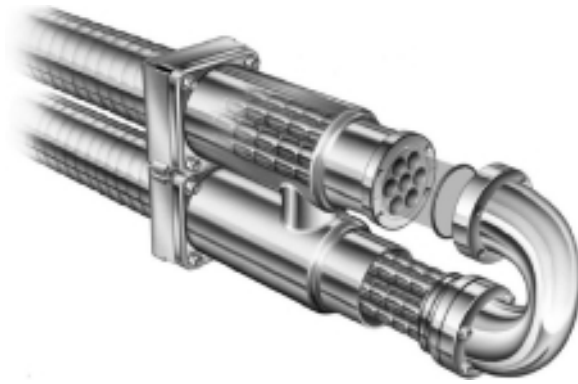
The above descriptions of flow behaviour and Reynolds number are very much a simplification of what is a highly complex and fascinating subject. However, they serve as an introduction to the subject and are the minimum information required for designing a holding tube in a continuous flow process.

### 7.2.2 Choice of heat exchanger

The choice of optimal heat exchanger depends to a great deal on the flow conditions. Fluids with low viscosities and no particulates are preferably treated in a plate heat exchanger (Fig. 7.11). This



**Fig. 7.11** Plate type heat exchanger (courtesy of Tetra Pak Processing Components AB).



**Fig. 7.12** Multi-tube type tubular heat exchanger (courtesy of Tetra Pak Processing Components AB).

should be the first choice of exchanger because of its low cost and high heat transfer rate. For fruit juices with pulp and fibres of up to 5 mm length, special types of plates are available with more open channels that allow the fibres to pass through unhindered. In addition, even with high viscosity foods, the plate heat exchanger can be utilised as long as the pressures developed are not too high and the rheological behaviour does not indicate that a yield stress is present. Foods that contain yield stresses can experience mal-distribution of flow between the plate gaps and in some instances this can lead to flow stagnation and blockages.

For fruit juices with fibres of up to 15 mm length and for relatively water-like foods, a multi-tube tubular heat exchanger is preferably used (Fig. 7.12). Also, fluids of moderate to high viscosity with only small particulates (<5 mm) will flow through a multi-tube heat exchanger without problems. Despite being less thermally efficient than a plate heat exchanger, multi-tubes can be configured in various options of the number of tubes in parallel and of tube diameter. This gives them a high degree of flexibility.

A common application for the multi-tube exchanger is milk sterilisation, despite the heat transfer disadvantages of tubes compared with plates. Tube bundles, containing large numbers of small diameter tubes in parallel, offer adequate thermal efficiency, with the benefit of cleanability without dismantling. A plate heat exchanger would need to be taken apart to remove the fouling deposits that build-up over several hours of processing. This increases the downtime and increases the chances of contamination being introduced with poorly fitted gaskets.

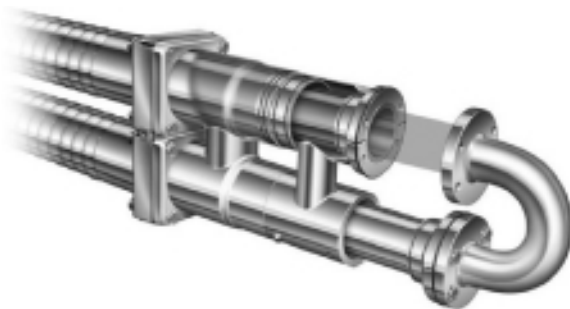
Most tubular heat exchangers now use corrugations on the shell and tubes to enhance heat transfer with the heating and cooling

media, typically water. Design of the corrugations will be specific to the company supplying the heat exchanger but they will each create the same effect, which is to generate turbulence in the water flows. This reduces the resistance to heat transfer caused by boundary layers that can be set up adjacent to the tube walls. In effect, it ensures that the media, whether it is heating water or cooling water, does not restrict the heat transfer performance of the exchanger. The limit to performance is therefore within the tubes.

The length of most commercial tubular systems has been standardised at 6 m, therefore tubular heat exchangers are long and thin in terms of their geometry. This makes them suitable for placement next to factory walls or even above head height. The need for access to the tubes is rare because the tubes themselves are designed to be cleaned in place and access will only be required to the connecting pipes and equipment. These can be positioned at ground level where access is easy.

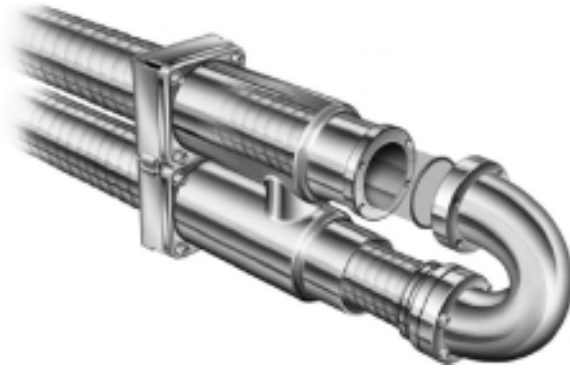
One of the greatest challenges to heat exchanger design is when the food fluids are significantly viscoelastic, i.e. exhibit a large yield value, often in combination with a high viscosity that is shear dependent. For these fluids, there is a risk of mal-distribution across the inner tubes of a multi-tube heat exchanger. In the worst case, the product flow will stop in some of the tubes causing overcooking of parts of the product and also cleaning problems where the food burns onto the inner tube surfaces. Examples of such products are hot break tomato pastes or stiff dessert puddings, where the multi-tube is not suitable and concentric tubes are a preferred choice (Fig. 7.13).

Concentric tubes have only one product channel, which eliminates the risk of mal-distribution. Here, the product flows in a gap between two concentric tubes with the media on both sides,



**Fig. 7.13** Concentric channel type heat exchanger (courtesy of Tetra Pak Processing Components AB).



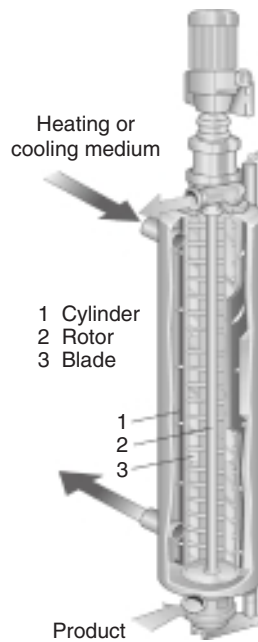


**Fig. 7.14** Mono-tube type tubular heat exchanger (courtesy of Tetra Pak Processing Components AB).

therefore increasing the heat transfer efficiency. Particulate products can be processed in wide gap modules, with particulate sizes up to 5 to 6 mm. Concentric tubes are a common choice of heat exchanger for tomato ketchup manufacture because this product possesses a yield stress that is an essential feature of the ketchup.

If large particulates are present in the food product, the mono-tube is probably the optimal choice (Fig. 7.14). The drawback with a mono-tube compared to a concentric tube or multi-tube is reduced thermal efficiency due to the thicker product layer. However, the particulates present in the product will to a great extent work as ‘internal mixers’ and will promote heat transfer. This makes design of mono-tube exchangers difficult, unless prior knowledge on the heat transfer behaviour of that food is available. The limiting design criterion for mono-tubes is the heat treatment given to the particulates, because of the need for heat to conduct into the particulate. The need for sufficient contact time between the carrier liquid and the particulates can be an advantage of the tubular concept, in which the food product has sufficient residence time in the exchanger to equilibrate towards a uniform temperature.

If none of the tubular types are suitable, a scraped surface heat exchanger is the last option (Fig. 7.15). In principle, a scraped surface heat exchanger is a mono-tube equipped with a rotating internal scraper. The scraper keeps the heating surface free from any deposits and also promotes turbulence. This type of heat exchanger is ideal for products of very high viscosity, possibly also containing large particulates, and especially for products that can foul the heated or cooled surfaces. Unlike tubes that usually



**Fig. 7.15** Scraped surface heat exchanger (courtesy of Tetra Pak Processing Components AB).

operate with water as the media, scraped surface heat exchangers often use steam for greater heat transfer efficiency. There are drawbacks with scraped surface heat exchangers in that the costs are high for purchasing a system and ongoing maintenance is higher than with tubular heat exchangers because they have moving parts that wear.

One common application for scraped surface heat exchangers is where cooled surfaces, without the scraping action, are likely to foul quickly as high viscosity layers develop on the surfaces or hard fats deposit. These will:

- insulate the cold surfaces from the product to be cooled and so reduce thermal efficiency; and
- reduce the effective cross-sectional area for flow, which will increase the velocity and again reduce thermal efficiency.

Continuous removal of these layers is essential for this application.

There are a small number of novel designs with scraping actions that do not conform with the typical heat exchangers described above. For example, UNICUS® is a tubular heat exchanger with a lateral scraped surface action, as is the ViscoLine dynamic unit.

Both have applications for products such as fruit and vegetable purées, pulps and concentrates, ketchup, dairy desserts, chocolate and UHT milk. Attempts have also been made to construct scraped plate systems so that the exchangers can benefit from very high surface areas and scraped surfaces kept free of fouling. The OCTATOR from Nova 2K is one example.

### **7.2.3 Maximising product recovery**

Food products have a high ingredient cost and so efforts are made to recover as much of the product as possible from the processing systems (Tucker and Shaw, 2001). Pigging systems for tubular heat exchangers are in widespread use in the food industry because of the high costs and high volume of product held up in the tubes. In a food application for a cook-in sauce product, this can be up to several tonnes of product. The simplest pigging system operates using air to displace the product. Complex geometries can be pigged using air at high pressure; however, high viscosity materials often require pressures too high for air systems. There is also a significant risk that the air will core through the centre of the flow channels where the material viscosity in a cooling application is at its lowest.

Pigs are usually made of plastic or plastic coated spheres that are pushed through the tubes by water or air pressure. Clearance between the pig and tube surfaces is only a few millimetres. They can go around 90° bends but cannot deform and pass through the gaps experienced in plate or scraped surface heat exchangers. These exchangers require a different type of pigging system such as a cheap material with similar physical properties to the food, for example a gelled starch. A recent development in deformable pigging options is the ice pig. It has an advantage over a starch pig in that the ice moves through the system as a solid plug with the boundary between ice and surfaces lubricated by a thin water layer. Recovery of expensive product is likely to be greater with the ice pig compared with a starch pig.

## **7.3 NEW THERMAL TECHNOLOGIES**

Food manufacturers are continually looking for new ways to produce food with enhanced flavour and nutritional characteristics. Traditional thermal processes using retorts or heat exchangers tend to reduce the vitamin content of food and can affect its texture, flavour and appearance (Holdsworth, 1997). There are many new

and emerging technologies that make great claims for their beneficial effects on food quality; however, few have reached commercialisation. Of these, only ohmic heating, high pressure and microwave processing have a role to play in niche thermal processing markets.

High pressure processing was originally considered in the 1890s, but it was not until the 1970s that Japanese food companies started to develop its commercial potential. Pressures of several thousand atmospheres (500–600 MPa) are used to kill microorganisms, but there is little evidence that high pressure is effective on spores or enzymes. Thus, chilled storage or high acidity are essential hurdles in preventing microbial growth. Jams were the first products to be produced in Japan, and the process is now being used commercially in Europe and the USA. Product types now include meats, fish and shellfish, and heat sensitive sauces such as avocado dips, fruit juices and smoothies.

High pressure sterilisation is still some way off, although there are patents that demonstrate possibilities for applying the technology to certain foods, including petfoods. The killing effect on *Clostridium botulinum* spores cannot be obtained with high pressure alone and so this effect will rely on thermal destruction. Most commercial equipment is batch, using vessels similar in appearance to medium-sized horizontal retorts.

Ohmic heating achieves its preservation action via thermal effects, but instead of applying external heat to a food as with in-pack or heat exchangers, an electric current is applied directly to the food. The electrical resistance of the food to the current causes it to heat it up in a similar way to a light bulb filament. The advantage is that much shorter heating times can be applied than would otherwise be possible, and so the food maintains more of its nutritional and flavour characteristics. The limitation is that ohmic cooling, or some other means of affecting rapid cooling, cannot be applied and so cooling relies on traditional methods that are slow in comparison with ohmic heating.

Foods containing large particulates are suited to ohmic heating because the electrical properties of the particulate and carrier liquid can be designed so that the particulate heats preferentially. The only commercial ohmic heater in operation in the UK (at the time of writing) is used to pasteurise fruit preparations, in which good particle definition is a key requirement. Most commercial ohmic applications are for high acid foods to avoid the requirement for aseptic filling. The technology has yet to find its niche market and the increase in applications has been slow. Nevertheless, for a high acid food with large particulates, ohmic heating confers

significant quality benefits when compared with conventional heat exchangers. One application that has yet to be explored fully is the use of ohmic heating for achieving the fill temperatures prior to hot filling into jars, cans or plastic packages. Hot filled products can be designed so they receive no further process and cooling occurs within the filled package. This is gentle on the particulates.

Microwave processing, like ohmic heating, destroys microorganisms via thermal effects. Frequencies of 950 and 2450 Hz are used to excite polar molecules, which produces thermal energy and increases temperature. On the continent, a small number of microwave pasteurisation units are in operation, primarily manufacturing pasta products in transparent plastic trays. Heat generated by the microwaves pasteurises the food and the package together, and the products are sold under chilled storage to achieve extended shelf-lives. Benefits of rapid heating can result in improved quality for foods that are sensitive to thermal degradation. The technology has not received widespread adoption because of the high capital costs of the equipment and the wide distribution in temperatures across a package.

Microwave sterilisation has not developed much because of the need for air overpressure to maintain the shape of the flexible packages during processing. This creates complications with continuous systems in that transfer valves are required between the chambers.

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## 8 Cook Values and Optimisation of Thermal Processes

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Thermal processing of foods has a dual purpose; first to commercially sterilise the product and second to cook it to an acceptable level. Unlike sterilisation, which has a precise objective, the term cooking may be defined in many ways. For example, it can refer to the softening of the product texture, retention of specific nutrients or vitamins, or a breakdown in a colour pigment. Thermal process times and temperatures are usually chosen so that a target F-value is achieved, and often to achieve a fast throughput. However, there are many products that require the cooking criteria to be taken into account, for example white sauces that turn brown easily if overcooked or foods containing delicate particulates such as fruit pieces.

This chapter addresses the challenges of maximising a specific quality attribute without reducing the thermal processing effect on microbial reduction. Examples are given on the different quality parameters appropriate to heat preserved foods and how these can be mathematically analysed. Examples are then presented to illustrate how process times and temperatures can be adjusted so that maximum quantities of a nutrient, such as a vitamin, are retained.

### 8.1 MATHEMATICAL ANALYSIS OF COOKING

Cooking processes can be considered in a similar mathematical way to microbiological destruction, by assuming they follow first-order reaction kinetics. This is not appropriate to all cooking reactions but sufficient reactions fall into this category that the analysis has merit. The first-order analysis becomes less accurate if chemical reactions occur during processing, for example with interactions between compounds present in the foods. Reaction orders are then based on the concentration of the reacting chemical species and this can result in more complex orders. These can still

be treated mathematically but are more complicated than with first-order systems (see Chapter 3 for explanation of first-order kinetics). The analysis that follows is appropriate for cooking reactions that can be approximated by first-order kinetics.

Compared with microorganism destruction, cooking rates have a different temperature coefficient of reaction or  $z$ -value. For example, whereas the rate of sterilisation processes increases 10-fold for every 10°C, the rate of change in many cooking processes is less for the same temperature change. Thus, there is a degree of incompatibility, because at low temperatures the sterilisation rates are slower than cooking rates, and this reverses at higher temperatures. For example, advantage is taken of this fact in the sterilisation of milk, which turns brown all too easily if heated for too long. In continuous flow heat exchangers, milk can be processed at high temperatures for short times (e.g. 135–140°C for 3–6 seconds) with minimal browning. Compare this with an in-pack process that has to operate at lower process temperatures (118–122°C) for longer hold times (10–20 minutes), and the result is an end-product with more browning.

Process optimisation is the task of judiciously selecting a process to give the desired degree of cooking but at the same time ensuring an adequate process value to take account of microbial destruction. There are many cooking attributes that can be used to optimise a heat process and it depends on the specific food product in the choice of which attribute is most relevant. Some of those reported to show first-order kinetics are:

- colour breakdown, e.g. reds and greens in canned vegetables;
- browning of white sauces and milk;
- meat texturisation;
- development of off-odours during processing;
- vitamin or nutrient retention;
- enzyme destruction.

Mathematical analysis of cooking follows a similar mechanism to that for the destruction of microorganisms by heat, as given in Chapter 3. The principle equations that govern this analysis are described below.

### 8.1.1 Cooking equations and kinetic data

The example equations presented here are for a sterilisation process, although the principles are equally applicable to pasteurisation. Thus, the symbols are for the unique sterilisation or  $F_0$ -value for the destruction of mesophilic *Clostridium botulinum* spores.

The sterilisation value of a thermal process ( $T_{\text{ref}} = 121.1^\circ\text{C}$ ,  $z = 10^\circ\text{C}$ ) is given by the integrated form in Equation 8.1:

$$F_0 = \int_0^t 10^{\frac{(T-121.1)}{10}} dt \quad (8.1)$$

If the product temperature ( $T$ ) is constant during the process, Equation 8.1 reduces to a simplified form of the equation (Equation 8.2). In thermal processing, the nearest example to this is found in a holding tube connected to a plate heat exchanger, for a product such as a thin liquid, such as milk or fruit juice. Heat transfer is very effective with thin liquids and so the liquid food increases in temperature very rapidly in the heat exchanger. Most of the lethal kill occurs during the time spent ( $t$ ) by the product at a fixed temperature ( $T$ ) in the holding tube:

$$F_0 = t \cdot 10^{\left(\frac{T-121.1}{10}\right)} \quad (8.2)$$

In a similar way to the sterilisation calculation, the cook value (C-value) can also be represented by an equation for first-order reaction kinetics. This is given by Equation 8.3, in which the times and temperatures are the same as those used in Equation 8.2. The difference between Equations 8.2 and 8.3 is in the  $z$ -value for the cooking reaction rate, which is often higher when dealing with a quality attribute, for example colour degradation, texture or vitamin retention. In Equation 8.3, a  $z$ -value of  $33^\circ\text{C}$  is chosen to illustrate the differences, which is a value representative of the destruction of thiamine (Table 8.1):

$$C = t \cdot 10^{\left(\frac{T-121.1}{33}\right)} \quad (8.3)$$

Tables 8.1, 8.2 and 8.3 present a selection of data on cooking attributes that can be used in process optimisation. Data in these tables was taken from Holdsworth (1997). All reaction rates are approximated by first-order kinetics. The tables are not intended as an exhaustive list of cooking attributes, but instead to illustrate a range of kinetic data associated with cooking analysis.

Table 8.1 lists the destruction of vitamins and shows two important characteristics; first that the  $D$ -values are much higher than those for microorganism destruction (e.g. the *C. botulinum*  $D_{121.1}$  value is 12.6 seconds) and second that the  $z$ -values are also much higher (e.g. the *C. botulinum*  $z$ -value is  $10^\circ\text{C}$ ). The fact that vitamin  $D$ -values are high indicates that these vitamins are more heat



**Table 8.1** Kinetic factors for vitamin destruction.

Heat sensitive vitamin	Temperature (°C)	D <sub>T</sub> -value (s)	z-value (°C)
<b>Vitamin A (beta carotene)</b>			
Beef liver	103–127	D <sub>122</sub> = 2400	23.0
Carrot juice	104–132	D <sub>104</sub> = 23 600	25.5
<b>Vitamin B1 (thiamine)</b>			
Buffer	109–150	D <sub>109</sub> = 9500	24.0
Carrots	109–150	D <sub>150</sub> = 830	22.0
Spinach	109–150	D <sub>150</sub> = 610	22.0
Pea puree	121.1	D <sub>121.1</sub> = 10 000	31.3
Lamb puree	109–150	D <sub>122</sub> = 710	25.0
Pork luncheon meat	100–127	D <sub>127</sub> = 6300	35.0
<b>Vitamin B6 (pyridoxine)</b>			
Cauliflower	106–138	D <sub>121</sub> = 24 000	43.0
<b>Pantothenic acid</b>			
Beef puree pH 5.4	118–143	D <sub>121.1</sub> = 138 000	35.8
Beef puree pH 7.0	118–143	D <sub>121.1</sub> = 135 000	19.3
<b>Folic acid</b>			
Apple juice	100–140	D <sub>140</sub> = 100 000	31.0
<b>Vitamin C (ascorbic acid)</b>			
Peas	110–132	D <sub>121.1</sub> = 50 000	18.0
Spinach	70–100	D <sub>100</sub> = 25 900	74.4

stable than commonly thought. For example, when fruit is cooked, the ascorbic acid or vitamin C content is reduced considerably, but this occurs through several mechanisms and its breakdown by heat is less significant than either leaching from the fruit into the cook-water or by oxidation.

Table 8.2 shows that enzymes display a wider variation in both D- and z-value than for the vitamins in Table 8.1. Much of the research on measurement of these values was done for the frozen foods industry, in which blanching is a key process step. Blanching serves the main purpose of inactivating enzymes that would otherwise break the food down during the delays before freezing and also, perhaps more importantly, during storage of the food by the consumer. Some enzymes, for example peroxidase from sources such as horseradish, are very heat stable and can cause issues with the structure regenerating after only partial inactivation in a pasteurisation process.

Table 8.3 contains data for three of the main pigments of relevance to thermally processed foods. Green pigments are important for canned vegetables, where they readily change colour to an

**Table 8.2** Kinetic factors for enzyme destruction.

Heat sensitive enzyme	Temperature (°C)	D <sub>T</sub> -value (s)	z-value(°C)
<b>Peroxidase</b>			
Horseradish	60–160	D <sub>120</sub> = 830	27.8
Potato puree	100–140	D <sub>120</sub> = 70	35.0
<b>Catalase</b>			
Spinach	60	D <sub>60</sub> = 60	8.3
<b>Lipoxygenase</b>			
Pea/soya	50–80	D <sub>77</sub> = 720	3.4
<b>Pectinesterase</b>			
Guava syrup pH 4.0	74–95	D <sub>96</sub> = 35	16.5
<b>Polyphenol oxidase</b>			
Potato	80–110	D <sub>89</sub> = 100	7.8

**Table 8.3** Kinetic factors for pigment destruction.

Heat sensitive pigment	Temperature (°C)	D <sub>T</sub> -value (s)	z-value (°C)
<b>Green (chlorophylls)</b>			
Green beans	80–148	D <sub>121.1</sub> = 1260	38.8
Peas	80–148	D <sub>121.1</sub> = 1500	39.4
<b>Red</b>			
Raspberry juice	78–108	D <sub>108</sub> = 7000	30.4
Grapes	76.7–121	D <sub>121</sub> = 7600	54.7
<b>Browning reactions</b>			
Chestnut paste darkening	105–128	D <sub>121.1</sub> = 141 000	24.6
Milk, hydromethyl furfural	105–160	D <sub>130</sub> = 12	26.7

undesirable grey shade. Canned peas and beans need careful processing regimes, which includes some degree of pH control to avoid undesirable colour changes. Red pigments from berries give fruit juices a characteristic bright colour but can turn brown if the processing regime is too severe. For example, strawberries turn from their fresh bright red colour towards a brown colour when canned, as well as undergoing an adverse structure breakdown.

One of the most studied colour reactions is that of browning in dairy products (Burton, 1955; Kessler and Fink, 1986). These works have defined the UHT sector in producing sterilised milk

products of a higher quality than can be produced by in-pack methods. Milk and dairy products are treated at ultra-high temperatures (135–140°C) for short times (3–6 seconds), so the sterilisation occurs in an instant but cooking reactions occur at a reduced rate. The example that follows explains how this competition between sterilisation and quality works.

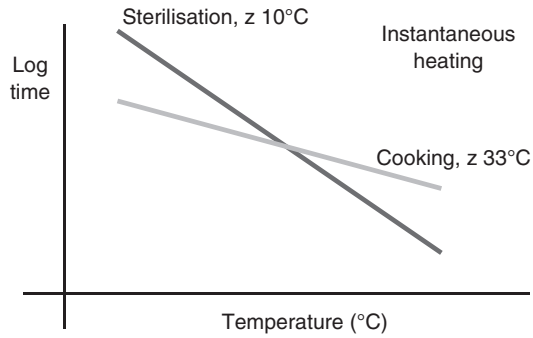
### **8.1.2 Competition between sterilisation and cooking**

The fact that *z*-values for microbiological safety and for quality attributes are often different by 10 to 20°C implies that the rate of these reactions occurs quite differently. Table 8.4 shows the calculated  $F_0$  and *C*-values for a unit time interval (1 minute), calculated from Equations 8.2 and 8.3. In effect, Table 8.4 presents the lethal rates at fixed process temperatures. The *z*-value for sterilisation is 10°C and the value of 33°C for cooking is appropriate to thiamine destruction.

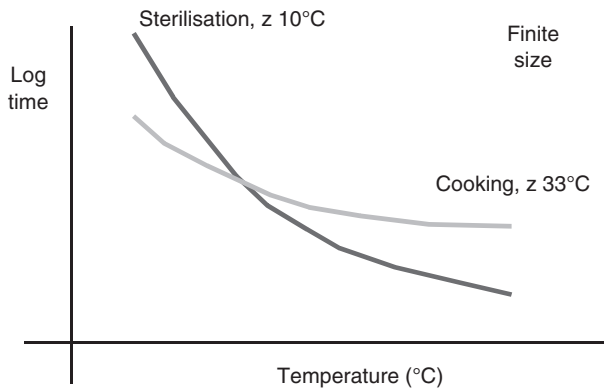
The  $F_0$  values in Table 8.4 increase by a factor of 10 for every 10°C rise in temperature, whereas the *C*-value approximately doubles for the same temperature increase. The effect of this difference can be seen more clearly if a plot of log time versus temperature is made (Fig. 8.1). Each of the two lines in Fig. 8.1 represents a line of constant *F*-value or *C*-value. At any point along either line, the *F*-value or *C*-value is the same. For example, the *F*-value line could represent  $F_{0.3}$  at any combination of process temperature and process time, and so the line indicates a division between a process that achieves a minimum botulinum cook and one that does not.

**Table 8.4** Effect on  $F_0$  and *C*-values of increasing the product temperature. Values represent the lethal rate for 1 minute at these temperatures.

<b>Temperature (°C)</b>	<b><math>F_0</math> value (minutes)</b>	<b><i>C</i>-value (minutes)</b>
100	$7.76 \times 10^{-3}$	0.23
105	$2.45 \times 10^{-2}$	0.32
110	$7.76 \times 10^{-2}$	0.46
115	$2.45 \times 10^{-1}$	0.65
120	$7.76 \times 10^{-1}$	0.92
121.1	1.00	1.00
125	2.45	1.30
130	7.76	1.85
135	24.54	2.62
140	77.62	3.71
145	245.4	5.25
150	776.2	7.42



**Fig. 8.1** Lines of constant  $F_0$  and C-value for foods instantaneously heated.



**Fig. 8.2** Lines of constant  $F_0$  and C-value for foods of finite size, calculated for a spherical food particle with radius 1 cm.

Data in Fig. 8.1 is for an imaginary product that heats instantaneously. This could apply to the heating of a thin layer of material whereby temperature rise is instantaneous, for example in the processing of a fruit juice in a plate heat exchanger. When the thickness of the material is considered, as in containers of food, the relationships become curved lines (Fig. 8.2), due to the need to integrate lethality or C-values under a time-temperature curve. Data for Fig. 8.2 were calculated for a spherical food particle with radius 1 cm, but a similar shape of graph applies to any in-container processed food product.

Despite the curvature in the lines, the regions for optimising the process times and temperatures still exist.

### 8.1.3 Optimisation of temperature/time in processing

Figures 8.1 or 8.2 can be used to highlight four processing regions in which the process temperature and time can be selected. This is the starting position for a process optimisation study that considers the cooking criteria when choosing the process temperature. It is essential that a minimum safety criterion or processing target is established, which is represented in Figs 8.1 and 8.2 by the sterilisation lines, and the process conditions must be chosen so that the process is above this line. This constrains the regions available for selecting the process time and temperature combinations to the two regions above the sterilisation line.

Worked example 8.1 shows how a process can be optimised to retain the maximum quantity of the vitamin thiamine.

#### **Worked example 8.1** Quality optimisation for a vitamin with z-value of 33°C (e.g. thiamine)

One cooking criteria that is often used in thermal processing is the retention of vitamins following the process. This is a good example to illustrate how a process can be optimised to retain the highest percentage of a specific vitamin. Thiamine typically has a z value of 25–33°C, much higher than for *C. botulinum* spores at 10°C, and so it is reasonable to expect the rates of destruction of thiamine and *C. botulinum* spores to occur at very different rates. When choosing the process temperature, it can be useful to consider what impact this has on the product quality. Table 8.5 presents some calculated options of process temperature and hold time that each result in a minimum botulinum cook for a canned pea puree product. These were calculated using the Campden BRI CTemp program based on a set of heat penetration data for pea puree at 121.1°C retort temperature.

Each of the above combinations of temperature and time were used as input parameters in the CTemp programme, so that cook values (C-value) could be calculated for a z value of 33°C using Equation 8.3. Conversion of the C-values to a number that represents the retention of thiamine uses another of the fundamental equations in thermal processing (Table 8.5). This equation relates the number of log reductions in the quality attribute (in this case thiamine) to a measure of the heat stability of thiamine, namely the D-value, as given in Equation 8.4:

**Table 8.5** Process temperatures and hold times that result in a minimum botulinum cook ( $F_03$ ) for 73 × 115 mm canned pea puree product.

Process temperature (°C)	Process time (minutes)
105	205
110	122
115	90
121.1	72
125	65
130	58

$$C = D_T \cdot \log \left( \frac{N_0}{N} \right) \quad (8.4)$$

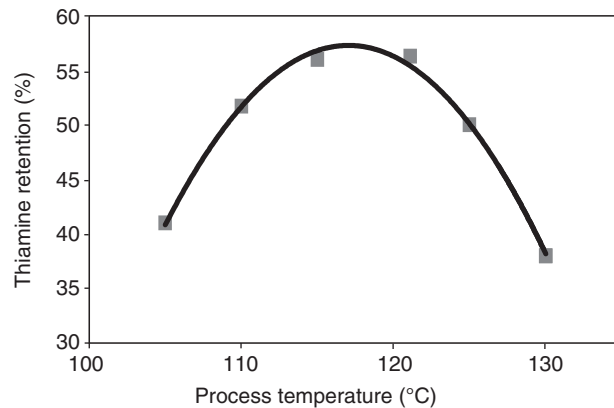
where  $D_T$  is the decimal reduction of thiamine, minutes,  $N_0$  is the initial thiamine concentration, mg per can and  $N$  is the final thiamine concentration, mg per can.

By rearranging the equation so the log reduction ratio is inverted ( $N/N_0$ ) and multiplying by 100 to bring the answer to a percentage, it is possible to calculate the % retention of thiamine in each can. Equation 8.5 presents the rearranged equation:

$$\frac{N}{N_0} = \frac{100}{10^{(C/D_T)}} \quad (8.5)$$

Equation 8.5 gives the percentage retention of thiamine directly and does not require either the initial or final concentration to be known. For thiamine retention, Table 8.1 gives a D-value of 166 minutes at 121.1°C. The calculated C-values for each temperature and time combination are substituted into Equation 8.5 to result in different percentage retention for thiamine.

Figure 8.3 presents the percentage retention of thiamine in the pea puree (conduction pack) for each of the equivalent *C. botulinum* processes. The optimised process requires a retort temperature between 115 and 121°C, in which around 55% of the thiamine is retained in the processed puree. Figure 8.3 also highlights the disadvantage of in-can HTST processing from a quality perspective.



**Fig. 8.3** Percentage thiamine retention for pea puree processed at various temperatures and times showing a process temperature optimum between 115 and 121°C.

The above worked example is for a very high viscosity conduction heating product in which minimal product movement can take place in the container. Hence, product towards the edges of the container will be exposed to much higher temperatures than at the centre, which can result in quality losses.

Not all products will show optimum process temperatures between 115 and 121°C. It will depend on the  $z$ -value for the quality attribute of interest, and on the rate of heating for the product. In general, fast heating convection products tend to show optimum processing temperatures higher than with conduction products. This is because the product can physically move within the container and this acts to even out the effects of exposure to time and temperature.

Retention of vitamins is only one criteria, and colour and flavour stability may also be limiting factors in selecting the optimal process temperatures for a product (Tables 8.1, 8.2 and 8.3). For example, in canned peas the minimum sterilisation times at 126.7°C in an agitating cooker produce a tough skinned product with unstable colour and flavour. At 126.7°C, the  $F_0$  value is 8 minutes that is equivalent to a  $C$  value of 30 minutes, sufficient to inactivate the enzyme peroxidase. At higher process temperatures than 126.7°C, in order to have the same effect on peroxidase, the  $F_0$  value must be higher than 8 minutes.

Another quality attribute of commercial importance to the fish industry is bone softening. Fish species such as mackerel and sardines are canned whole and the process has to be sufficient to

soften the bones. This is achieved by lowering the retort temperature to between 112 and 116°C, depending on can size and heat penetration rates, and processing for long times. It is not possible to produce an acceptable bone-in fish product using high retort temperatures and short times. The effect will be hard and sharp bones.

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## 9 Measurement and Validation of Thermal Processes

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Techniques for measuring thermal processes are described in this chapter, together with the process calculation methods used to establish safe times and temperatures. Measurement techniques for in-pack processes include temperature sensors of various types and log reduction methods that can be either microbiological or biochemical. Process calculation techniques are introduced, which allow process conditions to be calculated from the temperature measurements and analysis of deviations to be carried out. Differences in the techniques required for batch (in-pack) and continuous (in-flow) heat processes are described.

Temperature measurement systems are usually the first choice of validation method used by most companies. This is because of their ease of use, the greater quantity of information generated during the tests, and the relative expense when compared with a log reduction test. The methodology for temperature distribution and heat penetration testing evolved in the early part of the 1900s where mercury-in-glass thermometers were required. These tests were time-consuming and difficult to carry out, so process calculation methods were established that enabled results to be transferred from one set of conditions to another. The Ball method was one of the first examples to be derived and is still in regular use today.

The alternative is to use microbiological or biochemical log reduction methods, which are required where trailing wires and data loggers can interfere with the measurements. For example, continuous in-line processes for foods containing particulates or continuous oven and fryer processes (intended for products stored under refrigeration) require alternatives.

## 9.1 SETTING THE TARGET PROCESS VALUE

The first stage in a process validation study is to establish the processing targets based on a specific microorganism or group of microorganisms. Typical target organisms are considered in Chapters 1 to 5. Irrespective of the type of food, the target condition is to achieve commercial sterility for the product, which depends on the types and numbers of organisms present, both before and after the process, and on the intended storage conditions (DoH, 1994).

Thus, a process value ( $F$ ) is calculated from the decimal reduction time ( $D_T$ ) and the number of log reductions of surviving spores (Equation 9.1):

$$F = D_T \cdot \log \left( \frac{N_0}{N} \right) \quad (9.1)$$

where  $N_0$  is the initial number of organisms,  $N$  is the final number of organisms after a specific time-temperature history and  $D_T$  is the decimal reduction time at a fixed temperature ( $T$ ) to reduce the number of organisms by a factor of 10.

For example, for low acid, ambient stable products, spores of mesophilic *Clostridium botulinum* strains are the target. One of the guideline documents used by the UK food industry uses a starting number of 100 spores per unit mass or volume ( $N_0$ ) and a final number of  $10^{-12}$  spores (DoH, 1994). This starting number (100) represents a high level of contamination from *C. botulinum* spores, and would only be found in practice from poor quality raw materials or poor factory procedures. The final number ( $10^{-12}$ ) equates to a probability of 1 processed container in  $10^{12}$  containing a viable spore. The  $F$ -value for this process is given the specific terminology  $F_0$ . A  $D_{121.1}$  of 0.21 minutes is used in the UK and the calculation is rounded up to the nearest integer, in this case to  $F_0 3$ . This is the minimum process that should be given to low acid foods.

In commercial sterilisation processes, however, it is common to operate at substantially increased safety margins, using  $F_0$  values between 6 and 12 end of heating. These equate to log reductions between 18 and 36 (Equation 9.1). Pasteurisation processes, on the other hand, are usually operated to only 5 or 6 log reductions of the target organism, because of the presence of a preservation hurdle that lessens the chance of surviving organisms germinating from their spore form and/or the vegetative cells growing. There is

also an argument sometimes used that the target organisms for most pasteurisation processes are less lethal than *C. botulinum*. Caution is needed here because some chilled food processes target *Listeria*, *Salmonella*, *Escherichia coli* or psychrotrophic *C. botulinum* spores. All of these are pathogenic with high fatality rates. Further details on pasteurisation treatments can be found in Campden BRI (1992, 2006) and are discussed in Chapters 4 to 6.

Having calculated the target process value according to Equation 9.1, the thermal process achieved in the food containers is measured using temperature sensors or log reduction methods. These methods are discussed in the subsequent sections. The data are then used to calculate the achieved process value for the conditions evaluated, and if required, further calculations are carried out at worst case conditions. These enable the CCPs to be set for regular monitoring of the process.

## **9.2 VALIDATION METHODS: OBJECTIVES AND PRINCIPLES**

As mentioned above, the current thought process used by most food companies is to validate the microbiological process safety under ‘worst case conditions’ so that, by default, the process is safe under normal production conditions. Therefore, one of the key activities involved with establishing a thermal process is how to select the worst case conditions likely to be experienced during normal production. This approach avoids the need to probe up containers during each production run, which can result in misleading information.

### **9.2.1 How to select the worst case conditions**

It has been stated above that the process validation study should be conducted using worst case conditions. Therefore, by inference it should not be possible for a normal production batch to heat more slowly than the combination of factors evaluated as worst case. To determine the worst case conditions, it is necessary to consider the product, process and package separately, and to list all the factors that affect the heat transfer rate. The following lists suggest some of the factors that should be considered in a process validation study, although the lists are not intended to be exhaustive. These factors have been extracted from publications such as Campden BRI (1977, 1997a, 2008), Bee and Park (1978), NFPA (1985) and IFTPS (1995).

### 9.2.1.1 *Product*

- Formulation changes, including weight variation in ingredients that could lead to increased viscosity, e.g. high starch levels.
- Fill weight and in particular the % overfill of the key components, e.g. solids content.
- Initial temperature and the effects of delays in getting instrumented containers into the retort.
- Consistency or viscosity of the liquid components, both before and after processing.
- Size, shape and weight of solid components, both before and after processing, to determine the critical particle.
- Potential for matting and clumping of the solids, e.g. sliced mushrooms tend to stick together forming large clumps.
- Preparation methods, e.g. blanching that can affect particle density.
- Rehydration of dried components, e.g. dried rice that will heat more slowly than the hydrated form and also absorb water from the liquid.
- Heating mode for selection of probe positions in the container, whether the product heats by convection, conduction, mixed or broken heating.

### 9.2.1.2 *Container*

- Type of material, including metal cans, glass jars, plastic pouches and semi-rigid containers.
- Nesting possibilities with low profile containers, e.g. sardine cans.
- Vacuum and headspace that affect heat transfer through the top surface, and residual gases with flexible containers.
- Orientation the containers are loaded into the retort, e.g. symmetry of rotation.

### 9.2.1.3 *Retort or processing system*

- Mode of heating and cooling, and how it affects where the retort cold point is located, e.g. steam, steam/air, water immersion, raining water.
- Venting schedule, if steam.
- Overpressure profile and how this affects the volume of gas inside a flexible pack.
- Retort come-up time, which should be as short as possible to minimise the quantity of heat absorbed by the product during this phase.

- Racking and dividing systems that enable the containers to be supported but reduce the voidage for media to pass through.
- Rotation conditions.

The combination of conditions to arrive at the worst case conditions should be determined by a competent individual, sometimes referred to as a thermal process authority (specifically a US FDA term). It is not advisable to 'stress' each condition at its limit of variation, otherwise the containers used for process measurements will heat so slowly that all production will be grossly over-cooked. A balance between theoretical worst case and what is likely to happen in practice has to be obtained. This is where the skill of the individual has its value.

## 9.3 TEMPERATURE MEASUREMENT APPROACHES

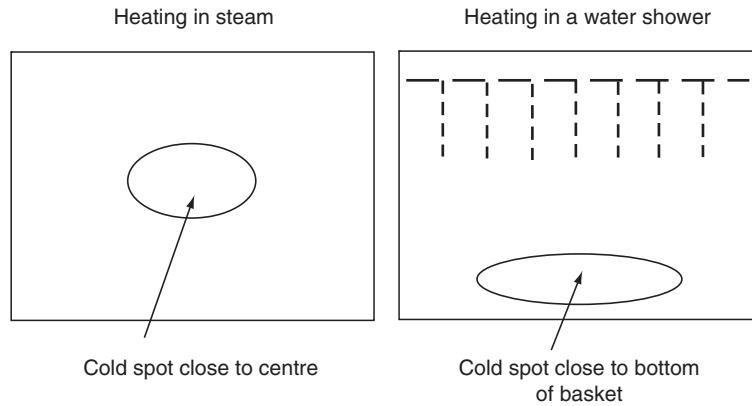
For an in-container process, there are two main stages in a process validation exercise:

- (i) *temperature distribution* (TD tests): to identify the location of the zone of slowest heating in the retort;
- (ii) *heat penetration* (HP tests): to measure the temperature response at the product cold point.

For a continuous flow process, a specialised form of the HP test is required, with various assumptions made regarding the positions of temperature measurement that make the TD test redundant. Continuous flow processes are described in Chapter 7 and so reference to the required techniques will be made here and readers are asked to refer to Chapter 7 for details of the processing equipment.

### 9.3.1 Temperature distribution tests

Any in-container processing system (retort, autoclave or steriliser) will contain regions in which the temperature of the heating medium is lower than that measured by the master temperature indicator (MTI). It is critical that food containers in these colder regions absorb sufficient heat to achieve the target process value. The location of these cold spots should be determined by performing TD tests throughout the system. Figure 9.1 illustrates an example of where the cold regions are likely to be found for steam and cascading water systems.



**Fig. 9.1** Likely retort cold spots for steam heating and cascading water heating.

The concepts for TD testing are simple; however, the practicalities of making the measurements are fraught with difficulty (IFTPS, 1992). For example, regions of low temperature may exist within a retort because of the flow restrictions imposed by the closely packed containers. Flexible pouches are notorious for restricting media flow because of their desire to expand to fit the available space. To position probes within a batch of food containers requires thermocouple wires to be trailed between the containers. This can open up the flow channels and can affect the TD results. These issues are overcome with remote logging systems (Ball Datatrace and Ellab Tracksense), but the downside of remote loggers is that results are not available until the loggers are removed and downloaded.

One cautionary word here that further complicates TD testing is that a uniform TD throughout the retort does not necessarily imply that heat transfer to the containers is also uniform. This relates to the poor heat transfer properties of air compared with steam or water.

However, uniformity in temperature is the minimum that should be studied and an additional heat distribution study is advisable if there are concerns about air entrapment or heat transfer coefficient reductions throughout a container load (Campden BRI, 1997b). Rotary retorts using excessive air overpressure are one example where the potential exists for air to collect at the crate centres. This occurs as a consequence of centrifugal effects of the heating media. This tends to be an issue only at high rotation speeds, perhaps upwards of 20rpm, and is likely to be more significant when the heating media is more dense than air,

for example with a water immersion, spray or cascading retort. A heat distribution test will need to use containers filled with a consistent material that heats at a similar rate to the product. Water and starch solutions are one option. With heat distribution tests being complicated to perform it is rare for companies to attempt them, and TD tests are usually all that are done.

The TD within a retort should be tested on its installation, with intermittent re-testing being required as factors change that could affect the retort performance. A suggested frequency for re-testing in the UK is every three years according to the Department of Health guidelines (DoH, 1994). Retorts require, as a minimum, re-testing in the event of engineering work likely to affect the TD of the retort, which could include:

- relocation of the retort or installation of another retort that uses the same services;
- modification to the steam, water or air supply;
- replacement of the key components, e.g. pumps and valves;
- repair or modification to water circulation or steam injection systems within the retort;
- if there are any doubts about the performance of the retort.

The Good Manufacturing Practice guidelines for TD tests in batch retorts, as defined in DoH (1994), are as follows:

In steady state operation, the temperature spread across the sterilising vessel should ideally be 1°C or less. However, when this degree of control is not achievable due to design or characteristics of the equipment, any deviation from the limit should be allowed for in the scheduled process.

### 9.3.2 Heat penetration tests

The aim of an HP study is to determine the heating and cooling behaviour of a specific product, in order to establish a safe thermal process regime and to provide the data to analyse process deviations. Design of the study must ensure that all of the critical factors are considered to deliver the thermal process to the product slowest heating point. The numbers of instrumented sample containers and replicate retort runs is subject to much discussion (Campden BRI, 1977; Bee and Park, 1978; NFPA, 1985; IFTPS, 1995), with the final decision linked to the measured variability between samples and between runs.

Modern data logging systems can provide the facility for taking multiple temperature measurements, therefore large quantities of



data can be taken more easily than was the case when the guidelines were first written in 1977 (Campden BRI, 1977). These recommendations were to use three samples in three replicate runs, providing a total of nine measurements. This  $3 \times 3$  system has served the industry for many years. The more common situation now is to take up to ten samples in two replicate runs, providing that the variability between runs is within acceptable limits (IFTPS, 1995). However, there can be limitations on the number of probes that can be inserted through a packaging gland or through the central shaft of a rotating system, and in these situations at least two replicate runs should be completed.

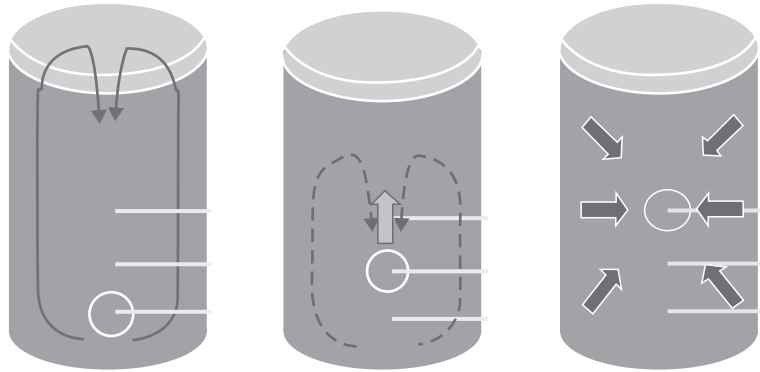
The HP study should be carried out prior to commencing production of a new product, a change in the process or the package. Changes to any of the criteria that may change the time-temperature response at the product slowest heating point will require a new HP study to be conducted. The conditions determined in the study are referred to as the scheduled heat process and must be followed for every production batch, with appropriate records taken to confirm that this was followed. No further temperature measurement within containers is required in production, although some companies do measure temperatures in single containers at defined frequencies. However, the conditions used in single container testing do not represent the worst case, and it would be expected that the instrumented container shows a process value higher than that measured from the HP study. Such data are intended to show due diligence and are at best a comfort factor.

An HP test is usually sub-divided into two further stages when conducting the tests:

- (i) first to locate the product cold point in the container; and
- (ii) second to establish the process conditions that will lead to the scheduled process.

#### 9.3.2.1 *Locating the product cold point*

Within each food container there will be a point or region that heats up more slowly than the rest. This is referred to as the 'slowest heating point' or 'thermal centre' and should be located using thermocouples or some other sensing method positioned at different places in a food container. For foods that heat mainly by conduction, the slowest heating point is at the container geometric centre. Also, if the process utilises rotation or agitation, the slowest heating point is forced to the container geometric centre.



**Fig. 9.2** Changes in the cold point location for a freely-moving liquid such as water, a mixed liquid such as a soup, and for a conduction heating product such as corned beef.

However, for foods that permit movement and heat by convection, this point is between the geometric centre and approximately one-tenth up from the base (in a static process). During the retort process, the food viscosity decreases in response to increasing temperature, and as a result the slowest heating point moves downwards from the container geometric centre. Figure 9.2 illustrates how the cold point changes with viscosity. The critical time in the process is when the lethal effect on the target micro-organisms is at its most significant, which is towards the end of the hold phase.

#### 9.3.2.2 *Establishing the scheduled process time and temperature*

The thermal process is finally established by measuring temperatures at the container slowest heating point for a number of replicates that are placed in the cold spot(s) of the thermal processing system. The data obtained are usually referred to as HP data. A point open to discussion is the number of replicates required for confidence in the data. As described earlier in this chapter, this depends on the variability between datasets, with  $3 \times 3$  and  $2 \times 10$  being common approaches.

## 9.4 PROCESS ESTABLISHMENT METHODS

The theory behind microbiological reductions by heat is that the kinetics is approximately first-order. Thus, an F-value calculated using Equation 9.1 will be the same as that calculated from the

time-temperature integration (Equation 9.2). Chapter 3 describes first-order kinetics in greater detail:

$$P \text{ or } F = \int_0^t 10^{\frac{T-T_{ref}}{z}} \cdot dt = D_T \cdot \log\left(\frac{N_0}{N}\right) \quad (9.2)$$

where  $T$  is the product temperature, °C,  $T_{ref}$  is the reference temperature for the  $D_T$  value, °C,  $t$  is the process time, minutes, and the kinetic factor,  $z$ , is the temperature change required to effect a 10-fold change if the  $D_T$  value, °C.

This integration is usually done within the data logger software, to allow a thermal process to be operated until the target F- or P-value is reached. This method is referred to as the General method. Other methods that use the measured times and temperatures within predictive models are also acceptable and used widely. The most common are the Ball method and its numerous derivatives, and numerical methods using finite differences, for example CTemp (Campden BRI) and NumeriCAL (JBT FoodTech). These methods give flexibility to evaluate the process for different input variables such as product initial temperature, process temperature and process time. Details of how each method works are not given here because of the complexities with using the methods. References are given at the end of this chapter to help those requiring information on the various methods.

In order that a process value can be calculated, it will need to be based on measurements of TD in the retort and HP in the product. TD is almost impossible to measure without temperature sensors; however, heat penetration usually uses temperature sensors but can also use log reduction methods. The next sections provide outline information on temperature measurement systems and log reduction methods, with references for further information should this be required.

### 9.4.1 Temperature measurement systems for TD and HP testing

Modern data loggers are typically multi-channel systems with digital outputs allowing data to be recorded directly to a laptop PC for display and to maintain permanent records. Thermocouples based on type T (copper/constantan) with PTFE insulation are most common because they are inexpensive, accurate over the desired temperature range, and respond rapidly to changing



**Fig. 9.3** Multi-channel system from Ellab that can be connected to 16 type T temperature sensors.



**Fig. 9.4** Ellab Tracksense.

temperature. Figure 9.3 shows a multi-channel system from Ellab that can be connected to 16 type T temperature sensors.

Other types of temperature measurement are based on a change in electrical resistance with temperature, such as thermistors and platinum resistance thermometers (PT100). These are most commonly used in data loggers where the logging unit is a self-contained unit (e.g. Ball Datatrace, TMI Orion, or Ellab Tracksense, as in Fig. 9.4). These are also referred to as resistance temperature detectors, or RTDs.

Calibration of a temperature sensor against a traceable instrument is essential, otherwise the user does not have confidence in

the numbers obtained. This is usually done each time the instrument is used in a set of TD or HP trials. The method recommended by IFTPS (1995) and Bee and Park (1978) is to use the master temperature indicator on the retort (MTI), which itself must be calibrated at no less than six-monthly intervals. It is worth noting that the new versions of Ellab Tracksense systems are claimed to hold the factory calibration for 12 months and are supplied with a calibration certificate.

The use of time and temperature measurements to validate thermal processes is likely to remain the most widely used method. Advances in microchip technology are providing more computing power to analyse these results and increase the accuracy in defining the calculated process values. Historic canning processes were evaluated using lethal rates at time steps of one minute, because of the capabilities of data recorders at that time, but modern process values can be estimated from temperature measurements taken at much reduced frequencies, for example every second. The increased data storage capabilities also allows for more temperature probes to be used in each TD or HP test, with multiple loggers linked together in the software. With such systems, it is possible to exceed the number of suggested working probes to define a HP test ( $3 \times 3$  or  $2 \times 10$ ).

#### 9.4.2 Log reduction methods for HP testing

There are two main techniques that are classified as log reduction methods, and these use:

- (i) microorganisms of known heat resistance, usually in spore form, in which the initial number (pre-process) and final number (post-process) are counted and used to calculate an F-value; and
- (ii) biochemical systems, in which the initial concentration (pre-process) and final concentration (post-process) are measured and used to calculate an F-value.

Figure 9.5 shows an example of both types of technique. The alginate spore beads can be prepared using a high proportion of food material, typically more than 90%, which ensures the beads behave in a similar manner to the food. The silicone tubes used for enclosing the biochemical solutions are chosen so the density and thermal properties also match those of the food.

Irrespective of which technique is used, it is critical that the z-value is close to that for the target microbial species, preferably



**Fig. 9.5** Picture of alginate spore beads and amylase TTI tubes.

within 2 to 3°C. If the z-value is not close, the processing temperature should be close to the reference temperature, otherwise significant errors can arise between values estimated using log reduction and with probes (from Equation 9.2). Also, the decimal reduction time should allow sufficient log reductions to be measured in order that the process can be calculated. A test that results in no surviving spores or no biochemical activity does not allow the process F-value to be calculated, and raises doubt as to where or when the total kill occurred. Some further detail is now given of each method.

#### 9.4.2.1 *Microbiological spore methods*

These are often referred to as direct methods, but they in fact rely on measuring the achieved log reductions for a process using a non-pathogenic microorganism and converting this to a process value for the target pathogen using Equation 9.1. No factory tests for sterilisation processes would use *C. botulinum* spores because of: (a) the hazards associated with handling these spores in a factory environment; and (b) the low numbers of spores that would survive the process. The latter point is easily illustrated from the theory of an  $F_03$  process that results in at least 12-log reductions in

*C. botulinum* spores. With almost all commercial processes operating to safety margins many times larger than  $F_{03}$ , surviving spores will not be present and will only occur when the process goes wrong.

Hence, a non-pathogenic organism with a high  $D_{121.1}$  value is used, for example spores of *Clostridium sporogenes* or *Bacillus stearothermophilus* (Table 9.1). An alternative is to use a gas-producing organism and estimate the severity of the process by the number of blown cans.

A microbiological method can be conducted using organisms distributed evenly throughout a food product (inoculation) or encapsulated in gel (alginate beads). The organisms are usually in their spore form because of the greater flexibility this provides in their use (Brown *et al.*, 1984).

An inoculation test measures the average thermal process in a container (see Worked example 9.1). If the product is liquid it is relatively easy to introduce the spores but for solid products it is necessary to first mix the spores into one of the ingredients to ensure that they are dispersed evenly throughout the container. Dispersion of the inoculum into the food dilutes the initial number of spores, usually to  $10^3$  to  $10^5$  per container, which reduces the F-value range that can be measured.

**Table 9.1** Possible marker organisms for use with microbiological log reduction methods for low acid foods.

Spore-forming organism	$T_{ref}$ (°C)	$D_T$ (minutes)	$z$ (°C)
<i>C. botulinum</i>	121.1	0.1–0.3	8–11
<i>C. sporogenes</i>	121.1	0.8–1.5	9–11
<i>B. stearothermophilus</i>	121.1	4–5	8–12
<i>B. subtilis</i>	121.1	0.1–1.0	10

**Worked example 9.1**

The following example for an inoculation test uses 1 g of spores of *C. sporogenes* supplied by a microbiology laboratory with a measured  $D_{121.1}$  value of 1.2 min and at a concentration of  $5 \times 10^7$  per g. The can of food for process measurement has a mass of 400 g. The question is ‘what is the maximum process value that can be measured with these spores?’

Equation 9.1 is used in the calculation:

$$F = D_T \cdot \log\left(\frac{N_0}{N}\right)$$

The initial numbers of spores in each can ( $N_0$ ) is diluted to  $5 \times 10^7/400$  or 125 000 spores per g. If we assume that the limit for spore numbers at the end of the process ( $N$ ) is unity (1), then the equation becomes:

$$F = 1.2 \log\left(\frac{125\,000}{1}\right) = 6.12$$

Hence, the maximum F-value that can be measured with these spores is 6.12 min.

### Worked example 9.2

The following example for an encapsulation test also uses spores of *C. sporogenes* with a measured  $D_{121.1}$  value of 1.2 mins and at a concentration of  $5 \times 10^7$  per g. The alginate bead weighs 0.2 g and is inserted at the centre of a 10 mm cube of carrot. The question is the same, which is ‘what is the maximum process value that can be measured with these spores?’

The initial numbers of spores in each bead ( $N_0$ ) is  $0.2 \times 5 \times 10^7$  or  $1 \times 10^7$  spores in the bead. The same limit for spore numbers at the end of the process ( $N$ ) applies (1), then the equation becomes:

$$F = 1.2 \log\left(\frac{10\,000\,000}{1}\right) = 8.4$$

Hence, the maximum F-value that can be measured with these spores is 8.4 min.

An encapsulation test allows the organisms to be placed at precise locations within a container or within a food particulate, by encapsulating spores in an alginate bead (see Worked example 9.2). The beads can be made with a high percentage of the food material



so the heating rate is similar to the food. This method is used for continuous processes where the food contains particulates that require evaluation at their centres. This is considered separately in Chapter 7. The number of spores per bead is usually greater than for an inoculation test and can be of the order of  $10^{6-8}$  per bead.

#### 9.4.2.2 Biochemical systems

These can be enzymes, such as amylase or peroxidase, which denature (an unwinding of the structure) during heating with similar kinetics to that of the target microbial species. Most enzyme systems are limited to pasteurisation because they are designed by microorganisms to operate at moderate temperatures. One exception is work by Tucker *et al.* (2007), in which amylase from the hyperthermophilic organism *Pyrococcus furiosus* is being used. This organism grows in saltwater pools in volcanic regions, such as Vulcano Island in Italy, and the amylase it secretes is naturally designed to be thermostable.

Calculation of pasteurisation or P-value uses the initial and final enzyme activities using Equation 9.3, which also assumes the first-order thermal death time model applies. This is the same equation for calculating integrated process values when using microbiological spore methods, except that the number of organisms is replaced by the amylase activity:

$$P = D_T \cdot \log \left( \frac{A_{\text{initial}}}{A_{\text{final}}} \right) \quad (9.3)$$

where  $A_{\text{final}}$  is the final activity after a specific time-temperature history,  $A_{\text{initial}}$  is the initial activity and  $D_T$  is the decimal reduction time to achieve a 1-log reduction in amylase activity, minutes.

Biochemical systems are often referred to as time-temperature integrators (TTIs), although strictly speaking the term TTI is also applicable to microbiological systems. Encapsulating the TTI is an essential step that prevents it coming into contact with the food or processing environment. One TTI encapsulation method (Tucker *et al.*, 2002) uses silicone tubing of 2.5 mm bore with the liquid TTI sealed in by silicone end plugs (Fig. 9.5). The amylase solution is recovered from the tube using a hypodermic syringe.

Amylase solutions are one of the few biochemical systems with appropriate kinetics (Tucker, 2000), which requires: (a) the D-value to be large enough for residual activity to remain after the process; and (b) the z-value to be in the 8 to 11°C range typically measured for microorganism death. Table 9.2 illustrates some of the key attributes of a specific amylase TTI system.

**Table 9.2** Key attributes of the *Bacillus amyloliquefaciens*  $\alpha$ -Amylase TT1.

Category	Description
Operating principle	Reduction in amylase activity in response to time and temperature
Measurement method	Amylase assay to measure absorbance rate, using a spectrophotometer
Active temperature range	60–100°C
Kinetic factor, or z-value	9.7 $\pm$ 0.3°C
Decimal reduction time	D <sub>80.7</sub> = 18.7 min
Process value	'pasteurisation-value'
Sample size	0.02 mL

## 9.5 PROCESS CALCULATION METHODS

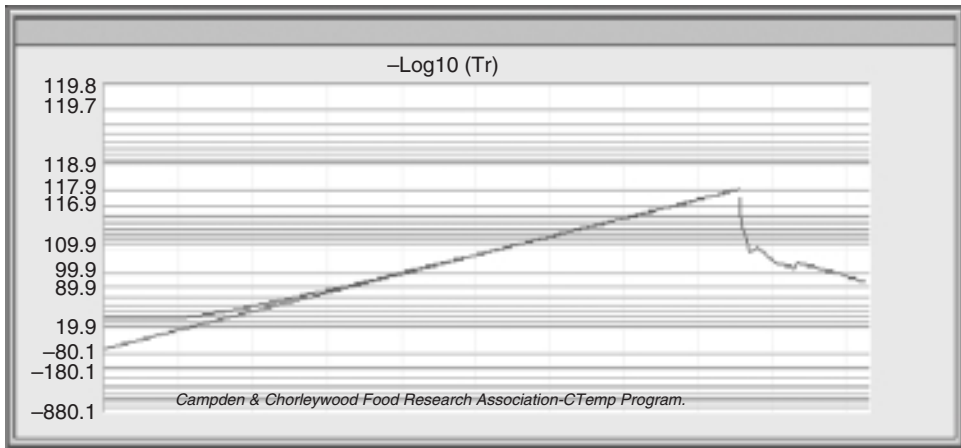
Several calculation methods are available for setting the scheduled process conditions. The most commonly used methods will be described in outline here, with the references provided for further information.

### 9.5.1 General method

The reference calculation method is known as the General method (Bigelow *et al.*, 1920) and it provides a process value (F-value) that is sometimes sufficient for validation purposes. It converts measured times and temperatures to F-values from accumulated lethal rates. A lethal rate is a relative term that compares the micro-organism killing effect at a measured temperature to one minute at a reference temperature (also discussed in Chapter 3). Equation 9.2 presents the lethal rate equation as part of the integrated F-value calculation, but the lethal rate ( $L$ ) itself is as given in Equation 9.4:

$$L = 10^{\frac{T-T_{\text{ref}}}{z}} \quad (9.4)$$

Integration of lethal rates over the measured times and temperatures is usually done using the trapezoidal method, with the calculation routines embedded within a data logger software. The General method allows the user to follow the F-value calculation during the process, usually in real time (with probes), but for loggers this is done when they are removed from the processing system. Time to achieve a target F-value is determined from the data and the process conditions can be established. While this is a simple method it does have some major limitations:



**Fig. 9.6** Example of a logarithmic heating curve for canned meat used to calculate  $f_h$  of 50.4 minutes and  $j$  of 1.45.

- F-values are relevant to the TD and HP test conditions on the day of testing and cannot be transferred to another set of conditions.
- Changes in critical variables cannot be evaluated without a new HP test, for example initial product temperature, retort temperature, come-up time, cooling profile.
- Deviations to the established process conditions cannot be evaluated by calculation and need to be experimentally simulated.

### 9.5.2 Ball method

For the above reasons, there are alternatives to the General method that are widely used in the industry. Apart from log reduction and General method calculations, all process calculation methods use heating ( $f_h$ ) and lag ( $j$ ) factors. Heating factors originated in the canning industry (Ball, 1923, 1927) as a measure of the product heating rate used for calculating process times for canned foods. By definition, the heating factor is the time taken for the difference between environment and product temperature to reduce by 90%. They are important terms in thermal process data analysis, because they provide information on the rate of heating for a container of food. Figure 9.6 shows an example of a logarithmic heating curve used to calculate  $f_h$  and  $j$  factors.

The Ball method is widely used within the USA and countries exporting thermally processed foods to the USA. Its use in Europe is less widespread. However, the Ball method offers options to the General method that enables some analysis of what-if scenarios to

be calculated. The Ball method has three parts to it and can be described in its most simple form as:

- (i) an equation to the straight heating line in Fig. 9.6, which is effectively the gradient at the end of heating,
- (ii) this is connected by an experimentally determined complex hyperbolic function to
- (iii) an equation to the straight line cooling line (not shown in Fig. 9.6).

The above description does not do the Ball method justice but does describe the constituent parts. The Ball method was derived for steam retorts because these were the main type used around the time Ball carried out his experiments (Ball, 1923, 1927). Hence the complex connecting routine between heating and cooling is most accurate for steam retorts and adjustments to this are required for other retort types, for example water retorts. It is important to note that the Ball method calculates an F-value at the end of cooling. Routines can be used to back calculate an end of heating F-value but these begin to lose their accuracy. If an end of heating F-value is required, then it is easier to use only the first equation to the heating part of the logarithmic heating curve, and express this as in Equation 9.5:

$$\frac{RT - T}{RT - IT} = j \cdot e^{-2.303t/f_h} \quad (9.5)$$

where  $j$  is the heating lag factor, defined as a measure of the thermal lag before the can temperature responds to the changing environment temperature (IFTPS, 1997), dimensionless,  $f_h$  is the heating factor, defined as the temperature response parameter derived from the logarithmic heating curve (IFTPS, 1997), minutes,  $RT$  is the retort temperature during the hold period, °C,  $IT$  is the product initial temperature at steam on, °C, and  $T$  is the product temperature after heating time ( $t$ ), °C.

Most Ball method calculations are now computerised versions of the tables and nomograms published by Ball (1923, 1927). Several attempts have been made since Ball to improve on the method, particularly for cooling lethality calculation.

### 9.5.3 Numerical methods

The use of more advanced mathematical models to evaluate and predict process times and temperatures have increased as the computing power available on desk-top PCs has increased.

Examples of numerical calculations are CTemp and NumeriCAL software, both of which utilise finite differences. These models deal with the physics of heat transfer and use finite differences to solve Fourier's partial differential equations. Therefore, they have a more scientific approach that allows variable retort profiles as the boundary conditions. This means that come-up and cool-down profiles can be defined as well as deviations in processes caused by retort temperature fluctuations (Tucker *et al.*, 1996).

These predictive modelling approaches not only help with deciding the fate for batches of product that have undergone a process deviation, but the task of process establishment is made more straightforward. The models can be used to evaluate changes to initial product temperatures, shortened come-up times or low retort temperatures. They offer considerable flexibility to make the job of process establishment easier.

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## 10 Cooling and Water Treatment

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The importance of water disinfection cannot be underestimated because it is arguably the single most significant public health measure of the last century (see examples in Chapters 1 and 3). Almost all types of microorganisms can be found in water, and water is most often the vehicle of transmission for these organisms. Treatment of water to make it safe for human consumption is therefore very important, and today there are standards set for potable water.

All water that comes into contact with foods should be safe, and comply with microbiological standards for drinking water. In canneries, the microbiology of the water used to cool the cans or other food containers is important (Warne, 1988; Downing, 1996). Contaminated cooling water can result in contamination of processed products in the containers. The cans (or other containers) are exposed to the water when still hot, and the seaming compound soft. As the metal cools a vacuum begins to form, which can result in minute amounts of water actually leaking into the containers. If the cooling water is contaminated, the containers are exposed to microorganisms at a time when the container is vulnerable. Bacteria or other microorganisms could enter the container, resulting in spoilage. If microorganisms such as *Escherichia coli*, other enteric bacteria, or mesophilic spore-forming bacteria are present in the water, it could make the product unfit for consumption. With contaminated can cooling water, leaker spoilage can often be found in cans, even with good quality double seams.

There are many ways that water can be rendered safe for food contact use and safe for use in the cannery. They are treatment with:

- (i) chlorine;
- (ii) bromine, with chlorine;



- (iii) ozone;
- (iv) ultraviolet light;
- (v) membrane filtration.

## 10.1 CHLORINE

Chlorine is used extensively as a disinfectant and oxidising agent in clean water applications. It is widely used as a disinfectant in swimming pools and cooling water recirculation systems. Typical applications include:

- potable water distribution systems;
- cooling tower recirculation water;
- swimming pool water;
- food and beverage processing.

When chlorine is dispersed in water, it hydrolyses very rapidly to form a variety of molecular and ionic species, which exist in a variety of forms, such as elemental chlorine ( $\text{Cl}_2$ ), hypochlorous acid ( $\text{HOCl}$ ), hypochlorite ion ( $\text{OCl}^-$ ) and substituted amines or chloramines ( $\text{NH}_{(3-x)}\text{Cl}_x$ ).

Of these, the reactively dominant species for most aqueous chlorination reactions is  $\text{HOCl}$ . The hypochlorous acid is a weak acid that dissociates to form  $\text{H}^+$  (hydrogen) and  $\text{OCl}^-$  (hypochlorite) ions, the concentrations of which are dependent on the pH of the solution.

Different forms of chlorine used in water treatment are  $\text{Cl}_2$  (chlorine gas),  $\text{Ca}(\text{OCl})_2$  (calcium hypochlorite) and  $(\text{NaOCl})$  sodium hypochlorite. The form of chlorine in aqueous solution influences the antimicrobial properties thereof. When elemental chlorine or hypochlorites are added to water, they undergo the following reactions:

- $\text{Cl}_2 (\text{g}) + \text{H}_2\text{O} \leftrightarrow \text{HOCl} + \text{H}^+ + \text{Cl}^-$
- $\text{NaOCl} + \text{H}_2\text{O} \leftrightarrow \text{HOCl} + \text{NaOH}$
- $\text{Ca}(\text{OCl})_2 + \text{H}_2\text{O} \leftrightarrow \text{HOCl} + \text{Ca}(\text{OH})_2$

The hypochlorous acid ( $\text{HOCl}$ ), being a weak acid, partially dissociates relative to the solution pH:



At pH 7.5, the concentrations of  $\text{HOCl}$  and  $\text{OCl}^-$  (hypochlorous ion) are approximately equal. Above pH 7.5 the  $\text{OCl}^-$  will

predominate and below pH 7.5 HOCl will be in a higher concentration. The relative concentration of HOCl is therefore dependent on solution pH.

The relative concentration of HOCl to  $\text{OCl}^-$  will also vary with temperature. As the temperature increases, the relative concentration of HOCl decreases.

The antimicrobial efficacy and sporicidal effectiveness of chlorine solutions decreases with increase in pH. HOCl is approximately 80 to 100% more effective than  $\text{OCl}^-$  in killing bacteria. It is clear that the activity of chlorine solutions is greatly affected by pH, with the greater activity at lower pH values.

### **10.1.1 Chlorine demand and residual chlorine**

When one or more forms of chlorine are added to water, the amount of chlorine remaining in the water is less than the amount originally added. This is because the water has a certain 'chlorine demand'. The chlorine demand is the chlorine dose minus the chlorine residual (chlorine in the solution after a given contact period). The residual chlorine may consist of two forms, combined chlorine and free chlorine. The term 'total chlorine' is used to refer to the sum of these two forms of chlorine.

$$\text{Total chlorine} = \text{combined chlorine} + \text{free chlorine}$$

HOCl,  $\text{OCl}^-$  and  $\text{Cl}_2$  are collectively referred to as free chlorine.

Ammonia ( $\text{NH}_3$ ) or organic nitrogen species (urea, proteins, etc.) that may be present in water react with the free chlorine to produce monochloramines and later dichloramines and trichloramines. These chlorinated ammonia compounds, as well as other chlorinated organic amines, represent the combined chlorine species.

The disinfection ability of combined chlorine is about 1% that of free chlorine. Combined chlorine species may also produce odour and taste problems in drinking water, and have been categorised as suspected carcinogens.

### **10.1.2 Using chlorine**

At the normal pH of cooling water, 'free' available chlorine is a more effective bactericide than 'combined' residual chlorine. It is usual to dose cooling water so that free available chlorine remains detectable after a contact time of 20 minutes. Excessive chlorination of cannery cooling waters is wasteful and it also should be

avoided because chlorine is corrosive to the metals used in construction of thermal processing vessels.

As the lethal effect of chlorination increases at low pH (where hypochlorous acid predominates), the acidity of the cooling water must be ensured, but there are practical constraints as to how low the pH can be, given that normal cannery cooling water is in the pH range of 6.5 to 8.5.

Temperature must also be considered because, at high temperatures, chlorine solubility is reduced, with the result that chlorine gas is driven off.

High levels of organic matter will increase chlorine demand and, like inorganic impurities, they also protect bacterial contaminants.

Under good manufacturing conditions, it is sufficient to maintain residual free available chlorine levels of 2 to 4 ppm after a 20-minute contact time in order to be confident of holding total aerobic counts at less than 100 organisms/ml of cooling water.

Free available chlorine should be still detectable in the cooling water at the completion of the cooling cycle. This is almost certain to be one of the CCPs in a cannery. For quality control purposes (and for the HACCP), records of free available chlorine levels should be maintained to provide confirmation that cooling water chlorination procedures were adequate.

### 10.1.3 Chlorine dioxide

Chlorine dioxide ( $\text{ClO}_2$ ) and chlorine are similar in many respects, including the fact that both are powerful oxidising agents.  $\text{ClO}_2$  has 2.5 times the oxidising capacity of  $\text{Cl}_2$ , and so  $\text{ClO}_2$  is an effective biocide. However, it is less effective than chlorine at equal concentrations when the organic content of the water is high.

Chlorine dioxide does not hydrolyse in aqueous solutions, and is therefore not subject to dissociation in the manner of hypochlorous or hypobromous acids. The  $\text{ClO}_2$  is the active biocidal compound.

## 10.2 BROMINE

Bromide is a common constituent of natural waters at concentrations in the range of fractions of a part per million. Bromine also exhibits biocidal properties in water, and is used as a water disinfectant, especially in cannery cooling waters. The bromine hydrolyses in water to give hypobromous acid ( $\text{HOBr}$ ).

Bromine is usually added to water in the form of sodium bromide (NaBr). This dissociates in solution to form  $\text{Na}^+$  and  $\text{Br}^-$  ions. Whenever chlorine or hypochlorite is added to water containing  $\text{Br}^-$ , there is a rapid formation of HOBr according to the reaction:



The resulting HOBr is also an electrophilic agent, but one that tends to react more rapidly than HOCl. It is therefore even more bacteriocidal than HOCl. Under alkaline conditions, hypobromous acid dissociates to form the hypobromite ion, just as hypochlorous acid forms the hypochlorite ion. However, the dissociation to  $\text{OBr}^-$  and  $\text{H}^+$  occurs at higher pH values. Bromine is therefore still effective (as a biocide) at much higher pH values than chlorine.

Much of the HOBr that reacts will be reduced to the bromide ion, to be reoxidised to HOBr by residual aqueous chlorine in the water. The overall result is an enhanced reactivity exhibited by aqueous chlorine in the presence of the bromide ion.

Bromination of cooling water is gaining popularity within Europe as the preferred biocide to chlorination.

## 10.3 OZONE

Ozone is a gas at ambient temperature, partially soluble in water and, like most gases, increases in solubility as the temperature of the water decreases. It is formed when oxygen molecules ( $\text{O}_2$ ) are ruptured (i.e. by lightning, or high energy ultraviolet rays) producing oxygen fragments, which unite with other oxygen fragments to produce ozone ( $\text{O}_3$ ). Ozone has the unique property of auto-decomposition, producing numerous free radical species, the most prominent being the hydroxyl free radical ( $\text{OH}^\bullet$ ). As the pH of the solutions containing molecular ozone increases, the rate of decomposition of molecular ozone to produce hydroxyl free radicals also increases, such that at pH 10, ozone decomposes instantaneously.

Although the resultant hydroxyl free radicals are powerful oxidants, their half-life is so short (milliseconds) that no significant concentration can occur. This means that the hydroxyl free radicals do not have a significant effect on the microbes. Thus, the presence of molecular ozone is necessary to ensure microbial sanitation. It therefore has virtually no residual effect.

The half-life of molecular ozone is relatively long (~12 hours), but in aqueous solution it depends almost entirely on the amount of

‘ozone demanding material’ in the water. The dirtier the water, the higher the content of ozone-demanding materials and the shorter the half-life of the ozone (and vice versa). Ozone is therefore often not optimal for use in can cooling water recirculation systems where the water may contain a lot of organic waste and other debris.

Ozone has certain advantages over other biocidal solutions, for example:

- It has been shown to be a more powerful disinfectant than chlorine for the deactivation of a large number of microorganisms. It is considered the most potent oxidising agent available for water and wastewater treatment.
- It has been used safely and effectively in water treatment for nine decades.
- It is generally recognised as safe for treatment of bottled water because it does not remain in the water for very long and can thus be considered a processing aid rather than an additive with no safety concerns about residual ozone.
- It leaves no toxic residue. Excess ozone will rapidly disappear through its spontaneous decomposition in solution.
- Low concentrations (0.1–4 ppm) are required to effect practical disinfection (amounts vary according to the amount of organic matter present).

The disadvantages of ozone include:

- In terms of water treatment, ozone is more expensive than chlorine or the alternatives. The lower production costs of chlorine (relative to ozone), and its ability to maintain a residual concentration in distribution or recirculation systems, favours the use of chlorine over ozone.
- Ozone reacts with rubber and various synthetic rubber compounds. Teflon seals should be used in water systems where ozone is used as a disinfectant.

## 10.4 ULTRAVIOLET LIGHT

Ultraviolet (UV) light has been successfully used for water disinfection in various food producing plants. This includes its use as a pasteurisation treatment for clear liquids such as bottled waters. UV light acts on microorganisms by disrupting the cell’s genetic material (DNA). Shortwave UV light irreversibly damages the nucleic acids, preventing reproduction and causing deactivation.

Unlike chemical methods, UV disinfection does not alter the taste, smell, pH or chemical composition of the water. UV treatment is regarded as a viable alternative to the use of chlorine in clean water applications. A major disadvantage of UV light is that it can only be used to treat clear water, and any organic matter or other debris will shield the microorganisms from the UV rays. Furthermore, the penetration of UV rays into the water is very restricted.

UV light is absorbed by ordinary glass, and the water has to flow through expensive quartz tubes during the irradiation stage.

The lifespan of UV lights, which are also expensive, are reasonably short. Because of these disadvantages, UV light is not often used in the treatment of cannery cooling waters.

## **10.5 MEMBRANE FILTRATION**

Membrane filtration is comparable, in capital cost and size, to a UV disinfection system, and effectively removes bacteria and larger microorganisms, although viruses will pass through the filters.

The main problems with membrane filtration systems are:

- They can only be used for clean water applications, as organic material and other debris will rapidly block the filters.
- The filters need to be replaced frequently due to blockage and ‘grow-through’, which increases the running cost considerably. Grow-through can occur when there is a massive build-up of microorganisms on the dirty side and the organisms literally grow through the membrane pores onto the clean side, causing downstream contamination.

Because of the above drawbacks, membrane filtration is unsuitable for use in can cooling water recirculation systems. It tends to find applications for removal of microorganisms in water-like food products, for example water, apple juice, milk and beer.

## **References**

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- Warne, D. (1988) *Manual on Fish Canning*. FAO Fisheries Technical Paper – T285. FAO, Rome.



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# 11 Handling Processing Deviations

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This chapter describes methods to assess whether a process deviation has made a critical impact on the commercial sterility or safety of a product. Calculation methods include historical formula methods such as Ball and more recent finite difference methods such as CTemp and NumeriCAL (Chapter 9).

An alternative to calculation is experimental assessment of the lethality achieved during a deviation using retort simulators. Their uses and applications are described.

## 11.1 WHAT CONSTITUTES A PROCESS DEVIATION

By definition, a process deviation is whenever the actual process is less than (or different to) the scheduled process or when any critical factor does not comply with that specified in the processing schedule.

The scheduled process is the document that states the process times and temperatures, which ensures that the product is processed adequately. In addition to the retort conditions, it also includes the critical control points (CCPs) for the product and packaging that are deemed essential for product safety. Sometimes there may be additional factors that ensure the product quality is acceptable.

All thermal processing factories will experience process deviations from time to time, and the long-term success of that factory depends on how these are managed. Good manufacturing practices for thermal processing procedures are critical in minimising deviations, as is the adherence to the HACCP plan. As retort control becomes more automated, the reliance on manual decisions is reduced with the result that the incidences of process deviations are also reduced.



Chapter 9 considered the methods for establishing safe processing conditions. These are usually calculated from process measurements that are taken under worst case conditions, and include such factors as retort come-up time, hold temperature and time, initial product temperature, fill weight, pH and  $a_w$ . This is not an exhaustive list and there are further details in Chapter 9. A deviation can occur when any of these factors go out of control.

Whenever there has been a deviation from the scheduled process for any canned low acid or acid food, the canner is obliged to set that product aside from other production and immediately evaluate the process with respect to that product potentially being a public health threat.

Such evaluation of the process given must be done by a competent thermal processing authority according to recognised procedures, using all the available critical data for that particular batch.

Complete records of product and processing must be kept of all aspects of any deviation and the action taken. If it is determined that the product is not a public health threat, then it may be distributed as normal, but if this cannot be guaranteed, then it must be destroyed under controlled conditions.

## 11.2 WHAT CAN GO WRONG

There are many reasons why deviations can occur. Below is a list of some of the general reasons with examples. This list is not all inclusive and there are other reasons why deviations could occur.

Failure or error in one or more of the basic processing parameters:

- low initial temperature – i.e. below the recommended minimum;
- low, but uniform, process medium temperature;
- shorter process time than the scheduled process states;
- incorrect scheduled process given to that product/can size.

Change in heating medium temperature during processing:

- momentary drops in temperature (due to loss in steam, etc.);
- long drops in heating temperature;
- excessive heating medium temperature fluctuation.

A failure in the retort operation:

- no venting cycle;
- improper venting cycle (too short);
- partially opened valves, low steam pressure;
- excessive water or air inside retort;
- wrong container packing or position.

Equipment malfunction or failure:

- inaccurate temperature monitoring devices;
- recorder chart malfunctioning;
- no ink in recorder chart;
- missing information records.

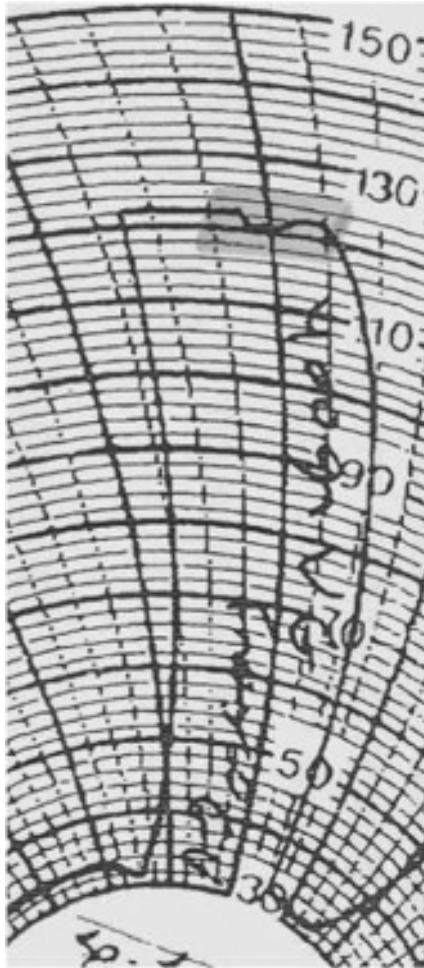
Product related errors:

- product out of specification with regard to critical factor (e.g. pH);
- product style variation;
- inadequate headspace in agitation is used;
- wrong ingredients/nett mass.

A thermal processing schedule is a document that defines all of the factors that must be controlled, so that a food product is processed safely. With so many factors needing to be controlled it is inevitable that, on occasion, one or more factors will fall outside of the acceptable limits. Table 11.1 gives examples of some of the

**Table 11.1** Examples of the more common process deviations experienced by canneries.

<b>Mechanical error</b>	<b>Possible impact</b>
Steam supply or boiler failure	Drop in retort temperature causing inadequate lethality
Instrumentation or air failure	Incorrect valve operation preventing the correct application of scheduled process. Poor pressure control causing packs to change shape during the process.
Automatic loader failure	Product stuck at different stages in the retort cycle, causing many issues such as low product initial temperature or inadequate cooling
Incorrect process (time/temperature) given to product	Inadequate lethality or excessive lethality causing quality issues
Incorrect product pH or $a_w$	Inadequate lethality or excessive lethality causing quality issues
Rotation or agitation stops	Reduced heat transfer resulting in inadequate lethality



**Fig. 11.1** Chart recording showing a process deviation caused by boiler failure during the process hold phase.

more common process deviations experienced by canneries. The consequences of some of these mechanical errors can be wide ranging, for example, air pressure failure will prevent valves from operating correctly as well as affecting overpressure control. Hence Table 11.1 is purely for illustration purposes and simplifies what can be a complex situation.

Despite the possibilities for there being many causes of a process deviation, the most common type is a failure in the steam system caused by boiler problems. This often results in a temporary drop in retort temperature while the boiler is down, as shown in Fig. 11.1. Often the downtime is only a few minutes because a

boiler is a critical part of most food production sites and demands immediate attention. In Fig. 11.1, the deviation is clear and lasted a few minutes before the retort temperature was restored to the set-point value.

### **11.3 ACTIONS REQUIRED**

In the unfortunate event of a process deviation occurring, there should be a procedure in place so that actions can be taken. This involves a number of steps, as described below:

- Put the product on hold pending investigation by the thermal processing authority (TPA) or approved persons, or extend the hold phase, or re-process immediately if appropriate for the product.
- Collect all the production records to provide a full description of the deviation for the TPA.
- Segregate the lot of containers that have undergone the process deviation and ensure they do not leave the factory.
- Contact the TPA so that a prompt analysis can be made.

The TPA term is one used by the US FDA and USDA and all companies exporting thermally processed foods to the USA. A processing authority is a person or organisation having expert knowledge of thermal processing requirements for foods packed in hermetically sealed containers and having adequate facilities to make these process determinations. Within European establishments it is more common for the Technical Manager or Quality Manager to act in this capacity.

Putting product on hold requires that the containers are clearly labelled and isolated from normal production containers where possible. A marked area should be available in all factories that produce thermally processed foods. A batch should be shrink wrapped to keep the containers together and avoid odd containers getting knocked off and rolling into areas where normal production is kept.

Until the deviation is analysed it is not possible to decide on the fate of the batch. If the containers have left the factory and are in the distribution chain, it will be a costly exercise to recover them for reprocessing or destruction. The worst scenario is for the containers to have reached the retailer shelves, which inevitably means that some will be with the consumers. Recalls at this stage also involve substantial adverse publicity but are extremely rare. The

few that have happened over the long history with canned foods have tended to be limited to isolated food poisoning outbreaks. Brand damage is so severe that a company will struggle to repair its image – as the following example proves (Box 11.1):

### **Box 11.1** Brand damage

In July 2007, two people in Texas and two in Indiana (USA) were made seriously ill and hospitalised with botulism poisoning suspected as originating from eating Castleberry's Hot Dog Chili Sauce. The precise cause of the incidents is not known but is suspected to have arisen from a series of process deviations due to improper functioning of retorts.

Although Castleberry recalled everything made on the one manufacturing line, the only products linked to illness were the chili sauces. The recalled products were sold under a multitude of brand names. Castleberry's Food Company is an establishment owned by Bumble Bee Foods LLC. Damage to the integrity of the Bumble Bee brand was also severe in addition to that for the brand names manufactured at Castleberry's Food Company.

### **11.3.1 TPA actions**

The TPA will require the documentation that describes what went wrong in the process deviation, in addition to documentation for the scheduled process. This includes the temperature distribution and heat penetration data taken during the process validation trials. It will be necessary to establish the process lethality delivered by the incorrect retort cycle and assess the adequacy for commercial sterilisation.

Decision making can be helped by process calculations of lethality generated during the process deviation (Fig. 11.2). There are several calculation methods that can be used, although the modern finite difference methods such as CTemp and NumeriCAL offer the greatest flexibility. Formula methods, such as Ball, are limited for most deviations because the method requires the lowest retort temperature to be used in the calculations. Worked example 11.1 illustrates how the Ball method results in a highly conservative assessment because of the low retort temperature reached during the deviation. Worked example 11.2 uses the CTemp program to calculate the effect of the deviation by using

the deviation time-temperature profile as the input to the calculations (see Worked examples 11.1 and 11.2):

### **Worked example 11.1** Process deviation caused by boiler failure – using the Ball method

Product is a pouch of egg fried rice processed in a steam-air retort for 35 min hold at 121°C to achieve an  $F_0$  6 end of heating. The process uses slow rotation at 2 rpm to tumble the rice and enhance heat transfer.

Heating factor ( $f_h$ ) 19.2 min, Lag factor ( $j$ ) 1.51

The process deviation was caused by boiler failure 10 min into the hold period. Retort temperature (RT) dropped from 121 to 80°C in 2 min, remained at 80°C for 5 min while the boiler was down, and was brought back up to 121°C in 3 min once the boiler was repaired. This was a similar deviation to the one illustrated by the chart in Fig. 11.1.

Deviation analysis using the Ball method requires a constant RT and so the process is re-calculated with a RT of 80°C, which gives:

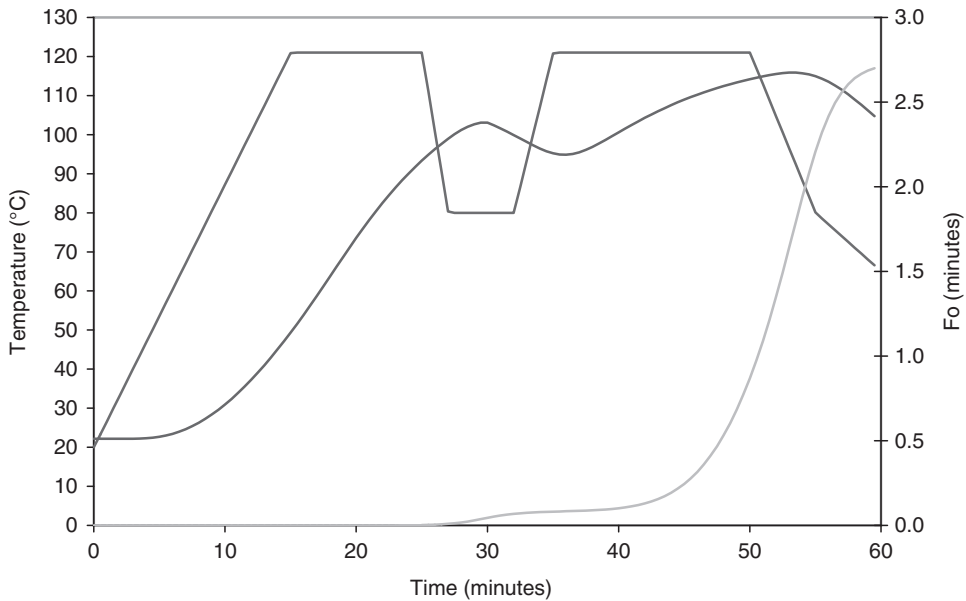
- $F_0$  after 35 min hold at 80°C;
- $F_0$  6 after 77.317 min hold at 80°C.

The calculated  $F_0$  after a 35 min hold at 80°C would result in the batch being thrown away. Also the Ball method cannot be used to calculate a processing time at the low RT of 80°C.

### **Worked example 11.2** Process deviation caused by boiler failure – using the CTemp method

The same product, process and deviation are used in this example but the analysis uses the CTemp program to calculate the effect of the boiler breakdown. Figure 11.2 shows an Excel graph taken from the CTemp predictions showing the drop in RT and its effect on the rice pouch temperature. With no extension to the 35 min hold, the end of heating lethality is below  $F_0$  1. Even with cooling lethality included in the analysis, the total  $F_0$  is less than 3.0.

The decision from the deviation analysis using CTemp is clear and the batch of product should be thrown away.



**Fig. 11.2** Time-temperature and time-lethality graph for the process deviation, showing  $F_0$  end of heating  $< 1.0$  and  $F_0$  end of cooling  $< 3.0$ .

Many companies apply simple rules for hold time extension when deviations such as a boiler breakdown occur. If steam supply is lost for a number of minutes it is common to add at least that number of minutes onto the hold time. Worked example 11.3 shows how this rule can be used in the rice pouch deviation.

**Worked example 11.3** Process deviation caused by boiler failure – using the CTemp method but with a 10 minute hold extension

The same product, process and deviation is used in this example and the analysis uses the CTemp program to calculate the effect of the boiler breakdown, but the hold time was extended by 10 min.

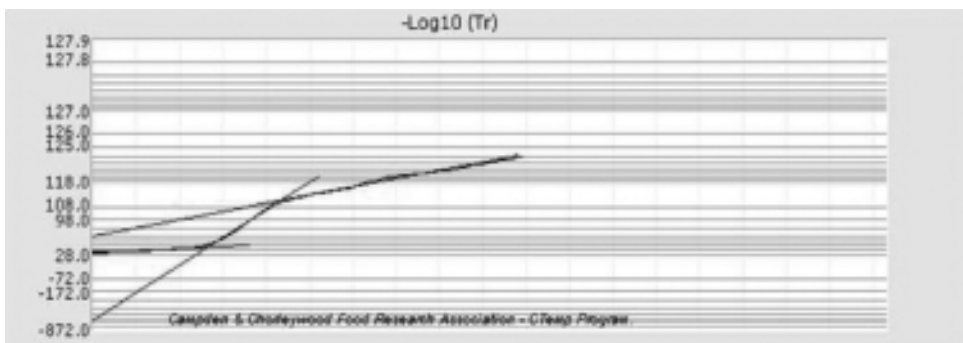
A 10 min extension to the 35 min hold time increases the end of heating  $F_0$  to 4.9 and the end of cooling  $F_0$  to 8.8. While  $F_0$  4.9 end of heating is less than the target of  $F_0$  6.0, it is still above the minimum botulinum cook of  $F_0$  3. Hence this batch is safe and can be distributed.

### 11.3.2 Process deviation analysis for broken heating products

The worked examples above are for a simple heating product; that is a product that only shows one rate of heating or heating factor ( $f_h$ ). These are the most common types of products in the industry. However, there are products that contain complex thickening agents, which change their viscosity so drastically that the heating rates change during processing from conduction to convection and vice-versa. Petfood chunks in gravy or jelly are examples, as are soups and sauces made using starches in their powder form. Figure 11.3 illustrates a semi-log plot (logarithmic heating curve) for a chunks-in-jelly petfood that shows two break points.

Within a process calculation model such as Ball or CTemp, the calculations use the time to reach each break point as the determining factor that fixes when the thermal properties change in the calculations. However, the time to each break point in Fig. 11.3 is not only determined by the time spent by the product in the retort, but also it is a function of the product temperature and shearing conditions within the product. For example, starch gelatinisation is a function of time, temperature and shear rate. A different set of conditions, as with a process deviation, can cause the break points to occur at different times. This makes calculation of the lethality during process deviations almost impossible if the process involved structure changes that are influenced by container agitation, and the integrated time-temperature relationship for the product.

Examples of foods that display broken heating points that depend on time, temperature and shear are those in which heat and mass transfer occur simultaneously within the product. Pulses that rehydrate in a sauce are classic examples, such as beans in tomato



**Fig. 11.3** Semi-log plot (logarithmic heating curve) for a chunks-in-jelly petfood showing two break points.





**Fig. 11.4** Pilot scale reel & spiral simulator.



**Fig. 11.5** Pilot scale hydrostat simulator (courtesy of Stork Food and Dairy Systems BV).

sauce, where starches leach out of the pulse and water diffuses in. Many of these foods are processed in reel & spiral cooker-coolers using high rates of intermittent can rotation. If the reel stops (a process deviation) then agitation of the product also stops and heat and mass transfer takes place at a different rate. This cannot be predicted using the types of models used for thermal process

analysis. Only a full computational fluid dynamics (CFD) solution can get close to calculating the temperature rise under these conditions.

If one of these complex products experiences a process deviation, it is not safe to attempt process calculations unless the product has gone through its last break in heating rate. After this last break point, there will not be any more changes in thermal properties and it is acceptable to calculate product temperatures, if a deviation has occurred. However, even though the thermal properties will be constant, calculations should not move too far from the original conditions, and severe deviations are best not modelled.

The alternative to process calculations is to experimentally recreate the deviation conditions in a retort simulator. With batch retorts this is relatively straightforward but with continuous retorts of the hydrostatic and reel & spiral types, this requires specialised pilot equipment. Figure 11.4 shows a pilot reel & spiral simulator and Fig. 11.5 a pilot hydrostat simulator.



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## 12 Packaging Options for Heat Preserved Foods

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Food preservation is about delaying the onset of natural degradation and biodeterioration. Biodeterioration may be as a result of the metabolic processes of one or many microorganisms or it can be caused by insect, rodent or bird damage. Besides biodeterioration, there is also natural degradation that occurs in foods caused by intrinsic enzymes; those enzymes present in the product that cause degradation or decay after death. For example, loss of food quality by intrinsic enzymes is an important topic, as it can cause quality deterioration and render food unacceptable. Food, whether slaughtered or picked, is therefore an active organic system that can react favourably or unfavourably with its packaging. Understanding packaging options and the way they work together with the product is therefore critical to the success of any food packaging system (Tucker, 2008).

The functions of packaging are to contain, protect, preserve, portion, inform, promote and make portable. The packaging options for thermally processed foods include metal (mainly tinplate, but some aluminium) and glass and specific plastics (laminates and composites) (Fig. 12.1).

The primary packaging is the packaging that is in direct contact with the food. The protection and preserving functions are arguably the most important functions of primary food packaging, as it must keep the food in good condition until it is sold and consumed. If adequately packaged, the shelf-life of food may be extended, which allows the natural life of the food to be prolonged. This enables consumers to have choice in terms of the food available, and so food resources can be more equitably distributed. Correct packaging prevents any wastage (such as leakage, damage or deterioration) that may occur during transportation and distribution. Good packaging and presentation encourages consumers to buy products (Fig. 12.2).



**Fig. 12.1** Selection of packaging types for thermally processed foods.



**Fig. 12.2** Display of packaged thermally processed foods in South Africa.

Primary packaging for heat preserved food requires the following attributes:

- able to hold a hermetic seal;
- able to withstand the process temperature;

- provide a physical barrier that can afford the food the required microbiological, gas and light barriers;
- able to withstand the physical stresses that it undergoes during processing;
- able to withstand the physical stresses of transport, storage and distribution;
- must not react adversely with the food.

## **12.1 METAL CONTAINERS**

The most common form of packaging for thermally processed products is the can. The strength and non-breakability of metal makes it an ideal material for food packaging. Metal is also an excellent light and gas barrier, is quick and easy to seal and can withstand the temperature extremes of food processing. Cans are made from tinplate, tin-free steel or aluminium.

### **12.1.1 Tin plate**

A base plate of low-carbon, mild steel, onto which a layer of tin is electrolytically deposited, is called tinplate. The tin coating imparts a degree of corrosion resistance to the steel base, which would otherwise readily rust. The thickness of tinplate varies, depending on the size of the cans that are to be manufactured and their intended application. It is usually between 0.15 and 0.25 mm thick. With the worldwide trend of minimising packaging and waste, the thickness of tinplate has progressively reduced. Nowadays, many cans are made from a thinner, stronger DR (double reduced) tinplate, where the steel sheet is cold rolled twice prior to being tin coated, compared with the SR (single reduced) tinplate that was the norm. Tin coating mass varies, according to end use and whether or not lacquers are to be applied, and ranges from around 1.4 to 14.0 g m<sup>-2</sup>.

Tinplate on which the tin coating mass is the same on each surface is known as equally coated plate (E), whereas plate with different tin coating masses on each surface is referred to as differentially coated plate (D). When specifying tin coating masses it is customary to quote for each surface (inside/outside for differentially coated plate). E1 means there is 2.8 g of tin per m<sup>2</sup> of plate; while D3/1 means that the tinplate is differentially coated and has 8.4 g of tin per m<sup>2</sup> of plate on one side, and 2.8 g of tin per m<sup>2</sup> on the other surface. Convention is that the first figure after D denotes the internal surface.

### 12.1.2 Tin free steel (TFS or ECCS)

The same mild carbon base plate, as is used for manufacturing tinplate, can be electro-chromium coated (a surface chromium/chromium oxide treatment) to produce tin-free steel. Plain TFS cannot be readily welded and it lacks the corrosion resistance of conventional tinplate (since there is no sacrificial protection of the steel by an outer layer of tin), but it provides an excellent key surface onto which can be applied protective lacquers. TFS is mainly used for two-piece draw-redraw (DRD) cans and sanitary ends (i.e. non-easy-opening ends).

### 12.1.3 Aluminium

Aluminium foil is extensively used for trays, films and laminates. It is also commonly used for the manufacture of drawn and wall ironed (DWI) beverage cans. Aluminium alloys are used to make beverage can ends, closures for food cans and some DRD food can bodies. It is easy to fabricate, is light weight and relatively inert, but lacks the strength of steel.

### 12.1.4 Protective coatings (lacquers)

Under certain circumstances, cans may be plain (unlacquered), but many food products are reactive and corrosive and so the can may require an inner protective coating. The primary function of internal lacquers is to protect the can from the contents, and also the contents from the can. Lacquers can extend the shelf-life of a product by reducing the rate of dissolution of tin by corrosive products, prevention or masking of sulphide staining, reducing the bleaching action of tin on colour, and reducing or preventing adhesion of the product to the can.

Internal food can lacquers should have the following characteristics:

- non-toxic;
- not affect the flavour or colour of the food;
- provide an effective barrier between food and container;
- easy to apply on tinplate;
- not peel off or blister during canned food sterilisation and storage;
- have mechanical resistance to can manufacturing operations;
- economical.

The internal lacquers have particular properties developed to meet the various product requirements. They are based on a wide

variety of resin types. Some of the resins occur naturally but most are produced by chemical synthesis.

The three main types of lacquers used on the interior of most food cans and ends are discussed below.

#### 12.1.4.1 *Vinyl lacquers*

These are very flexible, have good adhesion properties and are free from odour and taste. Although they are air-drying, vinyl lacquers are normally baked to accelerate drying. A disadvantage of vinyl lacquers is that they decompose at about 170 to 185°C when they are in contact with steel. They are therefore applied over an epoxy base coat.

Vinyl lacquers are not suitable for products that are processed in steam or water above 100°C because they take up water, which is known as 'blushing'.

#### 12.1.4.2 *Organosol lacquers*

These lacquers are dispersions of high molecular weight PVC resins in a hydrocarbon diluent. They also contain a plasticiser.

Advantages of organosol lacquers are that they are very flexible and are high temperature process resistant, unlike the vinyls. They also have a high solids content and are therefore cost effective, yielding good coverage.

Organosols can be pigmented with aluminium but they cannot be mixed with zinc. They are often used on full aperture tinplate easy-opening ends and on drawn cans.

#### 12.1.4.3 *Epoxy-phenolic lacquer*

These are the most commonly used lacquers. They are epoxy resins based on epichlorohydrin and bisphenol A (see Box 12.1). They are combined with phenolic resins, which are produced by the reaction of a phenol with formaldehyde. This combination gives a good lacquer with good flexibility, adhesion and chemical resistance. Epoxy-phenolics are cured by heat polymerisation (cross-linking) at temperatures of about 200°C.

Various additives may be incorporated in the lacquer to give it special properties. For instance, aluminium pigments or zinc oxide or zinc carbonate may be added to mask sulphide staining of the tinplate. Meat release agents may also be incorporated to help solid meat packs slide easily from the can on opening.



**Box 12.1** Bisphenol A (BPA)

Bisphenol A (BPA) is an organic monomer used to make many different plastic materials and resins. Minute traces of BPA can be found in a wide range of food products, because it is used in the production of polycarbonate and epoxy-phenolic resins, which are in turn used for food packaging (e.g. the lacquers of some food cans, linings of glass jar lids, bottle tops and water bottles). It is also used in the manufacture of baby bottles, compact discs, white dental fillings, nail polish, contact lenses, false teeth, adhesives, water pipes and flooring.

Bisphenol A diglycidyl ether (BADGE) is a chemical derivative of BPA used to make epoxy resins, which are used in many applications including food can lacquers. Over time, traces of bisphenol A can migrate from the packaging into food.

BPA and some of its derivatives mimic oestrogen and are endocrine disruptors. Endocrine Disrupting Chemicals (EDCs) have the capacity to mimic hormones and to interfere with the hormonal messaging systems that regulate our normal everyday body functions. It is suspected that these compounds can cause reproductive damage and birth defects and that their ingestion may lead to prostate and breast cancer (Breast Cancer UK, 2009).

In 2002, the safety of epoxy resin can coatings was confirmed by an analysis of the European Commission's Scientific Committee on Food (SCF). The SCF estimated total dietary intake of BPA from all food contact sources, including epoxy resin coatings, to be in the range of 0.00048 to 0.0016 mm/kg body weight per day, which is below the Tolerable Daily Intake set by the SCF of 0.05 mm/kg body weight per day (EFSA, 2007).

The potential human exposure to BPA from can coatings is therefore minimal and poses no known risk to human health. Can coatings have been and continue to be recognised as safe by the US Food and Drug Administration, the UK Food Standards Agency, the EU Scientific Committee on Food and other government bodies worldwide. Many studies on BPA and its derivatives are ongoing.

The Plastic Materials and Articles in Contact with Food (England) (No. 2) Regulations 2006 permit the use of BPA in

the manufacture of plastic materials and articles intended to come into contact with food, provided that no more than 0.6 mg/kg migrates into the food.

Plastic types; 1 (PET), 2 (high density polyethylene), 4 (low density polyethylene), 5 (polypropylene) and 6 (polystyrene) do not use BPA during polymerisation or package forming, and thus cannot leach the substance into food or beverages.

[www.Bishpenol-A.org](http://www.Bishpenol-A.org)

A disadvantage of epoxy phenolic lacquers is that they include bisphenol A, so minute traces of this compound and its derivatives may migrate to the food contents although, with strict manufacturing control, this can be contained to well within safe limits.

### 12.1.5 Internally plain (unlacquered) cans

In some instances, the reaction between the tinplate of the can and the product results in a beneficial reaction (the colour of some fruit and vegetables remains brighter and appears more 'natural', as in Fig. 12.3), making the product more desirable. For these types of products, internally plain cans, with a higher tin-coating mass are used. The overall shelf-life of these products is generally determined by the rate of tin pick-up from the can. The statutory maximum level of tin for tin pick-up differs from country to country in the range 150 to 250 ppm.

Tin pick-up is usually slow; approximately 20 ppm in the first month and 2 to 5 ppm per month thereafter can be used as a normal guideline, although it will vary for different products (see Box 12.2). The rate of tin pick-up is influenced by many factors including:

- amount of oxygen present (this is related to the headspace size and vacuum level);
- acidity of the product (lower pH usually results in more tin dissolution);
- types of acids present (different acids influence the reaction differently);
- presence of pigments;
- levels of nitrates and sulphides.



**Fig. 12.3** Fruit cans that do not use an internal lacquer.

**Box 12.2** Tin in food (UK, Food Standards Agency, 2002)

Canned foods make the biggest contribution to dietary intakes of tin. Although most foods contain very low concentrations of tin, usually below 10 mg/kg, the concentration in canned foods packed in internally plain cans will increase with time as a result of the gradual dissolution into the food of the tin coating.

High concentrations of tin in food irritate the digestive tract and may cause stomach upsets in sensitive people at tin concentrations above 200 mg/kg, with an increased risk of effects at concentrations above 250 mg/kg. Such high levels are seldom encountered. These effects, the symptoms of which include fever, headache, nausea, vomiting, diarrhoea, abdominal cramps and bloating, are short-term, with recovery expected soon after exposure. There are no long-term effects associated with occasional intakes from tin in the diet, even at the higher level.

### 12.1.6 External covering

Tinplate containers and ends may be supplied to a specific tin coating mass and with or without an external lacquer, depending on the end use and the environment that the can is going to have to withstand (e.g. hot humid conditions will require a top end can specification).

## 12.2 CAN CONSTRUCTION AND HANDLING

Metal cans are available in many shapes and sizes to suit all types of products. They can be made from two pieces or three pieces of metal.

**Three-piece cans** are manufactured from a rectangular piece of tinplate (known as a body blank), which is formed into a cylindrical shape and then joined along a vertical seam by welding. To this cylinder two ends are added, one by the can maker and the other is seamed on, after filling, by the canner. These are referred to as the maker's end and the canner's end, respectively.

**Two-piece cans** are made either by a draw and re-draw (DRD) process using aluminium, TFS or tinplate or by a draw and wall ironing (DWI) process using tinplate. DRD cans are made from circular blanks of pre-lacquered plate, which are first drawn into shallow cups and then re-drawn, once or twice depending on the cans final dimensions, causing an elongation of the wall and a simultaneous reduction of diameter. DWI cans are made from a similar process; however, the walls are stretched further by a wall ironing process carried out by a narrowing series of three tool rings.

Advantages of two-piece cans over three-piece cans is that they have no side seam, and only one double seam, thus reducing the risks of leakage arising from imperfect seam formation. Also excellent lacquer coverage is achieved as the DWI can is internally spray lacquered after fabrication, compared with roller coated as a flat sheet before can manufacture.

### 12.2.1 Product specification

The formulation of the product must be considered when choosing a can specification because the inclusion of certain ingredients or intrinsic compounds in the food can cause a change in product/container compatibility, which can affect the (product) container corrosion and required shelf-life.

The presence of nitrate in certain foods will result in accelerated corrosion and should be controlled to as low a level as possible. Pack nitrate levels should ideally be less than 10 mg/kg. If it is unavoidably higher, an appropriate can specification that will afford the required amount of protection must be chosen. With acid products ( $\text{pH} < 5.0$ ), packed into internally plain tinplate containers, the nitrate content of the product, as packed, should be less than 5 ppm, determined as nitrate.

Sulphur dioxide/sodium metabisulphite ( $\text{Na}_2\text{S}_2\text{O}_5$ ) is commonly used as a preservative with some fruit products. Excess sulphur dioxide may play a role in many corrosion reactions inside tinplate cans resulting in formation of tin sulphide, inhibition of tin dissolution, the promotion of iron corrosion, and the formation of hydrogen sulphide taints in the product. Sulphur dioxide should not be present in internally plain bodied cans, and should not exceed 15 ppm total  $\text{SO}_2$  in internally lacquered cans.

Some trace metals can also be corrosion accelerators and must be controlled if possible and at least known. Copper levels should not exceed 1 ppm in internally plain bodied cans.

### 12.2.2 Storage and handling of empty unused cans and ends

Cans and ends should be handled and stored with care to prevent damage that could compromise the final integrity. Storage areas should be free from dust, insects, damp, condensation problems and excessive heat (heat could dry out the compound in the ends and accelerate corrosion).

If there is significant difference in day and night temperature ( $5\text{--}7^\circ\text{C}$  difference) the storage areas should be closed to control the humidity and the packaging should be wrapped. Depending on the humidity, condensation could occur on the packaging, causing corrosion, especially on cut edges of the can and end, so-called warehouse sweating.

At all times during storage and conveying, care must be taken to minimise the impact and physical stresses on the can. Damaged flanges can result in defective seams and abuse can result in corrosion and/or spoilage.

Loose easy-opening ends or cans fitted with easy-opening ends must be treated even more carefully, as even slight damage to the tab or score may result in subsequent failure or leakage.

### 12.2.3 Cleaning of empty unused cans

Although there is very little microbiological build-up on empty unused cans and ends, they may become contaminated with a

variety of foreign objects and therefore good manufacturing practice dictates to clean all cans before filling. The most efficient way is by inversion and the use of air jets and/or potable water jets. If water is used, care must be taken not to leave wet cans for extended periods as corrosion may start. Sterilisation of the unused cans and ends is unnecessary as the canning process will eliminate the small microbial load that may be present.

#### **12.2.4 Double seam formation and inspection procedures**

The seam joining the can end and the body is known as the double seam. It is the formation of this hermetic seal that is critical if the container is to function correctly. Errors in or inadequately formed 'double seaming' can lead to leakage, and subsequent canned food spoilage.

The double seam is formed by interlocking the can body flange and the can end curl during two rolling actions. The first action roll curls the edge of the can end up and under the flange of the can body and folds the metal into five thicknesses while embedding the flange into the compound. During this operation the circumference about the edge of the can end is reduced causing the 'extra' metal to wrinkle. The second action roll flattens and tightens the seam so that the hermetic seal is formed. This action causes the wrinkles (formed in the first operation) to be ironed out while the compound is forced into any gaps between the metal surfaces (Fig. 12.4).

As product safety depends on the existence and maintenance of the hermetic seal, it is important that double seam formation is checked regularly during production; after all jams under the sealing machine, after adjustment to the machine, and after machine start-up following a long delay in production. Good manufacturing practice guidelines indicate that visual inspection of double seams should be at least every 30 minutes. A lot of information as to the quality of a double seam can be obtained by a visual and tactile examination of the rolled seam. Skilled operators can often see if the double seam is out of specification.

Full double seam tear down procedures should be followed on samples from for each seaming head at least every four hours. Can manufacturers and can seaming machine suppliers usually supply directions for seam formation and standards against which double seams are evaluated. The critical parameters of the double seam that must be controlled are:



**Fig. 12.4** Cross-section through a double seam.

- seam tightness (percentage tightness rating/wrinkle grade and free space);
- actual overlap;
- percentage bodyhook butting.

Deviations from the standard requires immediate corrective action.

### 12.2.5 Washing of filled cans

Containers should be washed with hot water after seaming to remove product residues from the outside of the can. This will reduce the risk of external corrosion during processing and prevent a build-up of product contamination in the sterilisation system.

For some fatty foods, detergents may be required in the can wash water. These must be specifically chosen so that they will not cause corrosion of the exterior of the can.

Cans with easy open ends, which have an oil based score protection system, should not be washed with water containing detergents, because this will reduce the effectiveness of the protective oil.

Cans with aluminium easy open ends should not be washed with water having high alkalinity, because residues can lead to

aluminium corrosion at sites of metal exposure on the tab and around the score line.

The wash water should not be too cold, because this can reduce the initial temperature of the cans. This is especially important with starch based hot filled products (e.g. sauces), as in extreme situations, cans being held in the cold wash water may change the pack heating characteristics.

### **12.2.6 Processing of cans**

Processing conditions for all containers, and particularly those with easy open ends, should be controlled to ensure that permanent deformation of the ends (peaking) does not occur during processing. The internal can pressure developed during processing is mostly counter-balanced by the external steam pressure. The differential or excess pressure inside the can should be insufficient to cause permanent deformation of the ends if the cans have been filled to achieve an acceptable final vacuum level and headspace and if the strength of the end is sufficient. At the end of processing, as cooling starts, if the retort pressure is suddenly relieved, the excess pressure within the can may cause peaking of the ends.

Generally, pressure cooling is required when cans of 73 mm, or greater, in diameter are processed at temperatures of 121°C (250°F) and above and cans of 153 mm in diameter are processed at temperatures of 110°C (230°F) and above.

Pressure cooling should always be used with easy-opening ends.

### **12.2.7 Cooling of cans**

‘Stackburn’ occurs when cans are packed, palletised and warehoused too hot, causing retention of heat in a stack of cans for long periods. This can result in microbial spoilage, deterioration of product quality, or accelerated corrosion.

Conversely, over-cooling will result in the cans failing to dry adequately, leading to external rusting and increased risk of post-process microbial contamination.

#### **12.2.7.1 Corrosion prevention**

The presence of air during the processing and cooling cycle may also exacerbate corrosion and must be excluded by adequate venting or exhausting at high enough temperatures (> 85°C).

Incorrect quality cannery water can give rise to corrosion at sites of exposed metal during any stage of the processing cycle, in



both steam and water, or after processing while the containers are still wet. In order to minimise corrosion and to reduce scale, a typical processing or cooling water should have the following attributes:

- pH 7.0–8.0;
- chloride + sulphate content  $\leq 100$  ppm;
- free halogen  $< 5$  ppm;
- hardness (as  $\text{CaCO}_3$ ) 30–150 ppm.

Soft water can result in a highly corrosive environment and should be treated with an appropriate water treatment system to minimise risks of corrosion.

It is essential that the easy open end is thoroughly dried immediately after cooling to prevent corrosion of the score and tab, independent of cooling water quality and treatment. Where cans are to be left in crates after cooling, it is preferable to limit water retention by sterilising the cans with the easy open end down.

Corrosion may occur on wet containers irrespective of water quality and treatment, and so it is critical that cans are dried as soon after processing as possible. Drying equipment should ensure that:

- as much water as possible is removed from the can and end, especially in the case of an easy open end, in particular from under the score and tab, preferably by use of twists and an air knife;
- the residual heat within the container (should be 35–40°C) can be used to complete drying of moisture remaining under the curled edges of the tab. If the residual heat is inadequate, a heated air stage should be used.

When cans are labelled and packed immediately after processing, there should be a residence time of at least two minutes during and after drying, but before packing, to allow for complete evaporation of moisture.

The main risks of inadequate drying are rusting of tinplate cans and ends, and stress corrosion cracking of the score of aluminium ends.

Wet cans should never be manually handled because there is the possibility of infecting the cans with microorganisms, through the cooling double seams before the hermetic seal stabilises.

### 12.2.8 Secondary packaging

All labels and secondary packaging that come into contact with the cans must be suitably non-corrosive. Label paper, paper board and adhesives must comply with certain levels for pH, chloride and sulphate measured on a water extract. These levels are generally accepted as pH 5.5 to 7.5, 0.05% as NaCl and 0.25% as  $\text{Na}_2\text{SO}_4$ , respectively.

Water based glues should not be applied in excess or at low temperatures, as drying is inhibited and corrosion or mould can result.

## 12.3 GLASS

Glass is one of the oldest packaging materials used for food. It is almost completely chemically inert and therefore is suitable for packing many products and all foods. The glass used for food packaging is approximately 70 to 74% silica ( $\text{SiO}_2$ ) and 15% sodium carbonate  $\text{Na}_2\text{CO}_3$  (added to silica to lower the melting point) by weight. It is known as soda-lime glass. It contains traces of aluminium ( $\text{Al}_2\text{O}_3$ ) and magnesium ( $\text{MgO}$ ) for better durability. Various compounds can also be added to give the glass some colour (to block out light from transmitting through the glass), for example  $\text{FeO}$  and  $\text{Cr}_2\text{O}_3$  will produce a green tint, and cobalt(II) oxide-aluminium oxide ( $\text{CoAl}_2\text{O}_4$ ) will result in blue glass (see Box 12.3).

### Box 12.3 Properties of glass

Glass is a super-cooled liquid (i.e. a liquid that solidifies without any significant structural changes). Although generally considered fragile, newly formed glass fibre actually has the strength to support twice the weight of an equivalent steel fibre. Unfortunately, in practice, glass only has about one thousandth of its theoretical strength because it is a liquid and so any defect will spread unhindered throughout its mass.

Glass is a poor conductor of heat and sudden changes in temperature ( $\Delta 60\text{--}65^\circ\text{C}$ ) may cause breakage due to heat shock. Sudden heating, which puts the surface of the glass under compression, is less dangerous than sudden cooling, which puts the surface in tension (Rees and Bettison, 1991).

The principles of processing in glass are basically the same as for cans, but there are certain modifications that are necessary to improve the thermal properties of glass, which make it less vulnerable to rapid changes in temperature of more than 60°C.

The advantages of glass are many and include the following:

- forms a 100% gas barrier;
- impervious to flavours and odours;
- imparts no migrating chemicals to the food products;
- is resistant to any chemical attack from food;
- can seal efficiently;
- relatively strong;
- allows the product to be viewed.

The main disadvantage of glass is that it can be broken and the broken pieces can be very sharp and constitute physical hazards. Other disadvantages are that clear glass is not a light barrier, so product deterioration can take place due to light (e.g. Vitamin B<sub>3</sub> and colour loss), although this can be overcome by using tinted glass. Also, it is relatively heavy and is not suitable for products that are to be frozen.

### 12.3.1 Glass manufacture

Glass containers for food are usually made from clear or flint glass (Bansal and Doremus, 1986) (see Box 12.4). The raw materials for a batch of glass are typically:

- |  |     |
|--|-----|
| ● Silica sand  | 45% |
| ● Soda ash   | 13% |
| ● Limestone  | 10% |
| ● Minor ingredients<br>(e.g. feldspar, calumite, selenium) | 2%  |
| ● Cullet   | 10% |

These are melted in a furnace at 1500°C. The molten glass is fed into container-forming machines. A gob of glass is loaded into a parison mould, which forms the blank shape of the container. It is then transferred to a blow mould to be blown into the final shape. Once formed, the hot containers (650°C) enter an annealing oven for controlled cooling. If they are allowed to cool too quickly they will develop internal stresses and will be more susceptible to impact damage. Treating the surface before (hot end – with a vapour of organic titanium or an inorganic tin compound) and

**Box 12.4** Recycled glass

Broken or waste glass is known as cullet. Glass is infinitively recyclable and does not affect the quality or integrity of the new product. Benefits of using cullet is that there are no fusion losses in the melting process, i.e. one ton of cullet will generate the ability to remake one ton of glass. Before recycled glass is melted, non-glass contaminants must be removed (e.g. metal caps, lids and neck rings, lead collars from wine and champagne bottles, stones and dirt).

Different colour glass must not be recycled together or they will affect the tint and properties of the new glass containers.

after (cold end – e.g. with oleic acid), the annealing ovens increases the strength and lubricity of the containers.

A glass container for thermal processing must be able to form a hermetic seal with the cap. The most important feature on the glass container for this to be possible is the sealing surface, which must be of exactly the right dimensions and be smooth.

**12.3.2 Closures for sealing glass food containers**

The suppliers of caps/closures will have the correct specific information for each product type, size and processing combination. Closures for glass containers are made with either lacquered tinplate, tin-free steel or aluminium, into which has been placed a flowed-in plastisol lining compound (or a rubber ring with a pry-off cap) that acts as a sealant between the glass rim surface (called the ‘finish’) and the cap. The type of sealing compound, glass neck finish and cap design are specific for different applications (Fig. 12.5).

For bottles, the main types are:

- crown caps;
- roll-on-pilfer-proof (ROPP) caps;
- snap-on caps;
- corks.

For jars to be thermally processed, the main types of caps are:

- twist-on-twist-off (TO) caps;
- push-on twist-off caps (PT).



**Fig. 12.5** Selection of glass food packages, showing a range of jar and cap designs.

All lids/caps should neither affect the product nor be affected by it and they should seal the container for its expected shelf-life. This is usually found by testing trial containers with the product to be packaged to make sure that there is no interaction between the pack and the product. Expert advice should also be sought from the packaging suppliers when selecting the type of closure to be used.

### 12.3.3 Sealing mechanisms

Like cans, glass must be hermetically sealed to prevent product contamination after sealing and thermal processing. The closure is held in place by the vacuum in the container and/or the friction between the glass finish and the cap. The sealing surface of the glass may be across the top of the finish as with twist caps, around the side of the finish as with pry-off caps or around both the top and side seals as with push-on twist-off (PT) caps. It is important that the glass sealing surface is free of defects and protected from damage, as otherwise there is an unacceptable risk that the container will leak and draw in contaminants.

It is recognised as good manufacturing practice to ensure that the diameter across the finish of the jar is less than that of the

diameter across the body of the container. This prevents the closure from suffering undue damage through striking the closures on adjacent containers as they move along conveyors. Fortunately, with most containers that have lost their hermetic seals prior to processing, the caps will fall off during retorting and thus alert operators to pack failure.

In addition to obvious loss of vacuum, other faults to be aware of when using glass include the following:

- *Cocked caps*: usually caused by mis-alignment of lug type closures while passing under the sealing machine, so that the lug sits on top of the thread rather than underneath it. Cocked caps are readily visible as part of the top of the closure is raised.
- *Crushed lugs*: occur when the sealing machine forces the lug of a twist cap down over the thread, rather than engaging it correctly, while winding the closure down onto the finish.
- *Stripped caps*: result when the cap is over-tightened so that the lugs strip and splay-out over the thread of the finish.
- *Tilted caps*: occur when pry-off and PT caps do not sit down uniformly on the finish.

### **12.3.4 Inspection procedures**

The frequency of inspecting for adequacy of seals with glass containers should be sufficient to ensure consistent formation of hermetic seals and defined opening torque. As a guide, this means that intervals between non-destructive testing should be no more than 30 minutes, while destructive testing should take place at least every 4 hours per sealer. In addition to this, visual inspection should follow every occasion that the capper jams. The results of all closure examinations should be recorded (see Box 12.5).

#### **Box 12.5** Tamper evidence

The vacuum inside the container, the hermetic seal, and the properties of tinplate and tin-free steel allows a feature to be designed into the cap where an audible pop and a visible deflection of a button in the cap occurs when the closure is first opened after processing. This is an excellent feature and can indicate if the container has been tampered with.

### **12.3.5 Packing and processing**

#### **12.3.5.1** *Inspection and preparation of containers*

All incoming glass containers must be inspected for cracks, chips and small bubbles in the glass, as these will weaken the container and result in breakage during processing. New jars and bottles should be rinsed with clean water. Care is needed to make sure that the containers are not heated too quickly, as the heat shock may cause them to break.

#### **12.3.5.2** *Filling*

If very high fill temperatures are used, the glass containers may have to be pre-warmed to prevent thermal shock. Fill temperatures of at least 65°C are recommended to ensure that there is an adequate vacuum generated in the container, and that the product is sufficiently de-aerated.

The initial fill temperature of the product should always be higher than the temperature of the process water at the start of the process.

Particulate foods may need to be blanched to remove entrapped air that could cause excessive pressure inside the container during processing. Similarly, some products (e.g. pastes) may need to be de-aerated.

Clean filling conditions must be used to prevent contamination of the sealing surface, as this could affect the integrity of the seal. Product on the outside of the jar could affect the grip on the outside of the container and therefore affect the capper performance.

The fill level should be consistent because different size headspaces can result in varying amounts of internal pressure build-up inside the container during processing. Generally a headspace of at least 6% (with a maximum of 10%) of the brimful capacity of the container is recommended.

#### **12.3.5.3** *Capping*

The choice of sealing compound in the cap is very important, because different compounds are designed for different processing temperatures and cap application styles (e.g. hand applied, steam flow closed, pressure processed, pasteurised, etc.). Suppliers of caps will have the correct specific information for each product type, size and processing combination.

The good performance of the capper is critical and must be controlled.

When using PT caps and sometimes with TO caps, steam is used to soften the sealing compound and to create a vacuum. The efficiency of the vacuum generation by steam is monitored by cold water vacuum checks, jars are filled to a nominal headspace of 10 to 12 mm with cold water and the vacuum in the jar is measured. It should be in the region of 65 kPa (50 cm Hg).

#### 12.3.5.4 *Atmospheric processing*

Pasteurised products can be processed in a steam tunnel or in a boiling water bath. Cooling must be done by water spray, with first warm water and then cooler water, to avoid heat shock.

#### 12.3.5.5 *Pressure processing*

Food in glass containers is usually pressure processed in full water immersion retorts. Sophisticated water spray retorts can also be used, providing that the retort temperature and pressure can be strictly controlled. Generally, food in glass containers is not processed above 121°C (NFPA, 1984).

Overpressure is required to ensure that the cap does not lift during processing. Too much overpressure can result in the sealing compound being 'cut through'. This is a condition that can lead to seal failure. A general rule for twist-off caps is that 70 to 80 kPa pressure, in excess of what is required to reach process temperature, should be maintained with sterile compressed air. The amount of overpressure required for PT caps is greater because there is no physical holding of the cap onto the jar. The correct overpressure for each product type and process temperature combination should be established, but a general rule is that the maximum that should be used is 220 kPa (32 psi) and the absolute maximum is 245 kPa (35 psi). Fluctuation of more than 20 kPa (3 psi) is not permissible.

To minimise pressure fluctuations during processing glass jars with caps, first ensure there is at least 15 cm of water above the top layer of jars, and second ensure there is at least 15 cm between the top of the water and the retort shell.

To ensure effective temperature distribution during processing, the process water should be recirculated from the bottom of the retort to the top during processing. As for processing cans, the quality of the retort water must be continually monitored and it should be sterilised using a system such as chlorination or bromination.



### 12.3.5.6 Cooling

At the end of the complete process cycle, the jars must not be removed from the retort until the product temperature is colder than it was at filling. This ensures the internal pressure is less than before the process and so the cap surface will be depressed further.

As for cans, over-cooling can result in the jar failing to dry adequately, leading to rusting of the cap (if scratched) and entrapment of water beneath the cap sides, which could go mouldy.

## 12.4 PLASTICS, FLEXIBLES AND LAMINATES

The term 'plastic' can refer to any of a group of synthetic or natural organic materials that may be shaped when soft and then hardened, including many types of resins, resinoids, polymers and cellulose derivatives. The development of plastics in general has revolutionised food packaging. Plastics are very versatile and can be engineered to replace most other packaging materials. Generally, plastics are lighter than glass or metal, they can be transparent or opaque, they can be very thin and flexible, or highly rigid (Hutton, 2003).

Plastic polymers are used to make many different packaging types. There are three main categories of plastic based packaging used for thermally processed foods. According to Codex Alimentarius:

- (i) A '**Flexible container**' means that the shape or contours of the filled, sealed container are affected by the enclosed product.
- (ii) A '**Semi-rigid container**' means that the shape or contours of the filled, sealed container are not affected by the enclosed product under normal atmospheric temperature and pressure but can be deformed by an external mechanical pressure of less than  $0.7 \text{ kg/cm}^2$  (10psig) (i.e. normal firm finger pressure).
- (iii) A '**Rigid container**' means that the shape or contours of the filled and sealed container are neither affected by the enclosed product nor deformed by an external mechanical pressure of up to  $0.7 \text{ kg/cm}^2$  (10psig) (i.e. normal firm finger pressure).

These sorts of containers can be made from various polymers or laminated or co-extruded materials (various plastic polymers, paper and/or aluminum) and has been one of the major packaging growth areas in recent years; both in technological and materials advances and in actual market share. Packaging films are used to construct the packages for many different types of convenience foods. Some

important material properties are necessary to meet the requirements of these demanding convenience markets and include:

- a balance between toughness and stiffness;
- high strength and puncture and tear resistance;
- high temperature resistance ( $>130^{\circ}\text{C}$  is required for some reheat/cook-in-package applications);
- barrier properties (e.g. moisture, gas, odour, light);
- grease resistance;
- sealability;
- aesthetic properties and printability;
- processability/machineability (balanced surface friction);
- environmental friendliness (including recyclability).

### **12.4.1 Advantages of retortable plastics**

There are several advantages proposed for plastic containers, which include the following:

- Transport and storage of flat, empty pouches is compact, thus cheaper than for cans.
- Filling lines can easily be changed to accommodate different sizes.
- Pouch dimensions allow rapid heat penetration and therefore faster sterilisation, resulting in energy savings during processing (note that rapid agitation in rigid cans can provide heat transfer benefits far greater than can be achieved by thin geometry pouches).
- Short processing times result in better product quality (although the comment above is also relevant for rapid agitation with cans).
- The product is commercially sterile and therefore requires no specialised storage conditions (e.g. refrigeration).
- Pouches are easy to open, either by tearing or cutting.
- The pouch web material cannot corrode and therefore no rusting of the container can occur.

### **12.4.2 Disadvantages of retortable plastics**

Each container type (e.g. metal, glass or plastic) also has its disadvantages, which includes the following:

- The capital investment in the equipment for pouch manufacture and processing is large.

- Production/filling speed is generally slower than competitor packaging (realistically, about half that of cans).
- Heat processing is complex (temperature and overpressure control) and therefore the retort design is more critical and expensive.
- As the pouch is not rigid, some solid products lose their shape.
- Gentler handling of the packed pouch is required to ensure that the integrity is not compromised.
- The shelf-life of products in pouches is usually less than that of cans, and is dependent on the barrier properties of flexible materials.

### **12.4.3 Polymers used for retortable packaging**

#### **12.4.3.1 Polypropylene (PP)**

PP is very popular for retortable containers, because it is a microwavable package and a good water vapour barrier. However, it is a relatively poor gas (e.g. oxygen and carbon dioxide) barrier. Where longer shelf-life is required, PP is often used together with a barrier material such as EVOH (see section below). It is used for rigid plastic pots/bowls and bottles for various sterilised products, as well as part of the structure in some laminated films.

#### **12.4.3.2 Polyethylene terephthalate (PET)**

PET is the most commonly used polymer of a group called polyesters. It is a medium to high oxygen barrier, and has good strength and chemical resistance. It is an important polymer used in retortable packaging. In order to make PET resistant to high temperature, so it is suitable for retorting, it is used in the crystalline form.

#### **12.4.3.3 Ethylvinylalcohol (EVOH)**

EVOH is an important barrier polymer in packaging. EVOH, like other barrier materials has very poor mechanical strength, so is only used in multilayer applications. It has very high resistance to oxygen in its dry state, which is significantly reduced as the moisture content increases. When used together with PP in a multilayer application, the EVOH becomes wet during processing (moisture barrier properties of PP are poor at high temperature), so higher

levels of EVOH have to be used, compared with when it is used in non-retortable packaging.

#### 12.4.3.4 *Polyvinylidene chloride (PVDC)*

PVDC is an important barrier polymer. It is not affected by moisture in the same way as EVOH and is therefore a better barrier in retort applications.

#### 12.4.3.5 *Polyamide (PA)*

Nylons belong to the group of PA polymers. Nylon-6 is often used in food packaging because of its overall superiority in the combination of cost, physical properties and process adaptability. All PA have good barrier properties, although not as good as EVOH and PVDC.

#### 12.4.3.6 *Aluminium*

Although not a polymer, aluminium foil is very important as a barrier material for retortable packaging. Its main advantage is that it is an excellent gas and moisture barrier, and this does not change at the high temperatures of retort processing. The main disadvantage is that it lacks physical strength and flexibility and can form pinholes and cracks. The opacity of aluminium foil can be regarded as an advantage or a disadvantage. Where the product requires a light barrier, it will be an advantage, but if the customer would like to see the product, it is a disadvantage.

#### 12.4.3.7 *Glass-coated barrier films*

Films treated with silica oxide provide excellent barrier properties as well as transparency and microwavability. Many of the recent developments in retortable films contain transparent plastic materials coated with aluminium or silica oxides.

### **12.4.4 Types of packages used for thermally processed foods**

#### 12.4.4.1 *Retort pouches*

Arguably a successor to the tinplate can, the materials and manufacturing technology of retort pouches have had an enormous amount of work put into them to allow them to be able to compete in this highly sensitive food sector, where food safety and stability are paramount.



**Fig. 12.6** Retortable pouches.

The standard food pouch is a pillow pouch, which is made by heat sealing on three sides, leaving an opening through which to fill the pouch, and closure is done by a final, simple heat sealing operation. Pouches are made from flexible web stock that has the appropriate properties for the specific application (Fig. 12.6 and Example 12.1). They are usually made from the appropriate, printed flexible web and filled in one operation on a form-fill-seal machine. Pouches can also be pre-made, loaded into a magazine then filled and sealed by the packer.

The stand-up pouch (SUP) is a flexible pouch, with a bottom gusset that can stand erect without external support when filled, and has become a highly desirable packaging option. The stand-up feature of the standard pouch makes it able to compete ably with cans and cartons for ambient shelf-stable, dry and chilled products. SUP manufacture is fairly complex. Whether made from monolayer or multilayer materials (depending on use), the structure suffers from stresses of gravity and uneven weight distribution from the contents. The side walls must have engineered stiffness and strength and the seals and adhesives must be able to withstand temperature (low and/or high), physical and fatigue abuse.

**Example 12.1** Retort pouches for tuna

An example of the construction of one of the current tuna retort pouches is as follows: Cast polypropylene as the inner food contact layer (it has a good heat seal surface, is flexible, strong and is food compatible). This is followed by an aluminium foil layer that provides a light, gas and odour barrier, which determines the shelf-life of the product and also gives the pouch stiffness and allows for the tear notch. The next layer is nylon, which provides abrasion resistance. Finally the outside layer is polyester, which provides the high temperature resistance, toughness and the printability of the material (Hydrick, 2003).

To be able to differentiate the retort pouch and offer a clear window to see the product, alternate non-metal, barrier materials have been developed to replace the aluminium foil (e.g. Silica oxide on PET by plasma or vacuum depositing).

Depending on the final use of the package (i.e. required to withstand pasteurisation conditions  $< 100^{\circ}\text{C}$  or sterilisation conditions  $110\text{--}122^{\circ}\text{C}$ ), different films and laminates are used. Regardless of the use, the package must provide a strong hermetic seal, which should normally be at least 3 mm wide and continuous. For heat sealing, the sealing surfaces should be plane-parallel to each other and the temperature of the jaw should be uniform across the entire sealing area. Since the integrity of the heat seal is critical to the safety of the product, it should be tested routinely. Typical testing protocols include:

- seal strength tests, normally used to determine the best combination of time temperature and seal pressure;
- burst-pressure tests;
- seal thickness tests;
- dye penetration tests;
- visual appraisal of seal quality (no creases, bubbles, etc.).

Whether considering flexible retort pouches, semi-rigid or rigid packs, all of these options offer the common attraction of providing a means to minimise the nutritional and sensory quality losses that often are associated with traditional thermal processing in rigid containers, while simultaneously providing the opportunity to display visually appealing products.

#### 12.4.4.2 *Plastic cans and pots*

Foil free rigid plastic containers are particularly desirable for the ready-meal market, because the shelf-stable product can be microwave heated in its packaging prior to consumption. Such bowls/trays are generally opaque, and made from laminates to give the desired shelf-life (usually 12–24 months). Clear pots and bottles are often used for fruit to display the cut style and fruit colour.

For convenience foods, the desirable attributes of these packs are:

- to be easy-to-open;
- to have a hermetic seal;
- to be easy to fill seal and process;
- to provide an adequate barrier for the required shelf-life;
- to be aesthetically pleasing.

#### 12.4.4.3 *Retortable composite carton*

Recently, retortable cartons designed for shelf-stable food products have been produced ([www.tetrapak.com](http://www.tetrapak.com)). They were designed as an alternative to the metal can for foods such as beans, vegetables, tomatoes, soups and sauces. The main advantages are efficient shelf-space usage; square packages are easily aligned on the shelf for a greater brand impact and they are also easy to open. They are made from pre-printed aluminium foil, laminate based board. The thermal process is very similar to that for cans and jars using overpressure.

### 12.4.5 **Processing considerations – control of headspace**

Rigid plastic pots are generally sealed with flexible lidding material, and so the amount of headspace entrapped inside the package must be controlled, otherwise too much will result in excessive pressure created during processing at high temperatures. To minimise the effect of pressure build-up, these sorts of containers are processed with overpressure, typically 1 bar over the retort pressure for that temperature.

Foil or film laminates are usually used, bonded to the container by heat, induction or ultrasound sealing (Box 12.6). The laminate structure and types of adhesives are specifically chosen for product

**Box 12.6** Induction sealing

Induction sealing is a non-contact method of heating multi-layer laminated foil lidding film, to hermetically seal plastic and glass containers.

Although direct application or sometimes 'cap-less' induction sealing can be used, most frequently a plastic 'over-cap' is supplied to the packer with a multilayer foil liner already inserted. The top layer is a paper pulp that is generally spot-glued to the cap. The next layer is an adhesive that is used to bond a layer of aluminium foil to the pulp. The bottom layer is a polymer film laminated to the foil. Once applied, the container passes under an induction coil, which emits an oscillating electromagnetic field that causes the conductive aluminium foil to heat. The heat melts the adhesive, and releases the foil from the over-cap. The polymer film layer also heats and melts onto the container sealing surface. When cooled, the polymer creates a bond with the container, resulting in a hermetically sealed product. The total time taken is in the order of a few seconds.

Sealing can be done with either a hand held unit or on a conveyor system. Care must be taken to ensure that the correct pulse, exposure time and top pressure is used for the specific seal and lidding system, as it is possible to over- or under-heat the film.

type and process temperature. The sealing conditions are also very specific for product type and lidding system.

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## 13 Incubation Testing

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Incubation of processed packs is commonplace in the food industry; however, a variety of incubation practices occur, which suggests that there is no standardised approach. This chapter will describe the objectives of incubation together with some recommendations for times and temperatures that different types of microorganism require. It includes suggestions for sample size and methods for interpretation of results.

Incubation tests are used for a variety of reasons that are explained later. They can provide information on the adequacy of a thermal process, particularly for spoilage microorganisms; however, their value for determining whether food safety organisms have survived a process is less certain and so incubation should not be used as the sole criterion of product safety. As described in several chapters in this book, the assurance of product safety is achieved through a properly developed and implemented HACCP programme (Chapter 14).

### 13.1 PURPOSE OF INCUBATION TESTS

Incubation testing is intended to identify surviving microorganisms within a container of food that has undergone a thermal process. These organisms are likely to be present in very small numbers, unless there is a gross processing or container fault, and so the first step in incubation is to grow the surviving microorganisms to reach numbers so that they can be detected. A variety of holding times and temperatures can be used to achieve this, and the choice depends on which group of microorganisms is of interest. Times and temperatures for incubation are discussed later in this chapter.

There are several reasons why a company would wish to undertake incubation tests on thermally processed foods. For example:

- if a process is thought to be of marginal severity, possibly as a result of a process deviation;
- if leaker spoilage is suspected, based on results of seam evaluation or seal testing, or from poor microbial quality of cooling water;
- if new package types or packaging materials are being evaluated, which may include different types of closure, and information on the seal integrity needs to be generated and assessed;
- if different raw materials are being used for the food product and there are concerns that heat resistant spoilage organisms may be present;
- it is a legal requirement in some countries;
- some customers require incubation testing as standard.

Spoilage of thermally processed foods occurs from time to time and it is important to understand what caused the containers to spoil so that it can be avoided in future. If spoilage has occurred, results from an incubation test can identify the types of organism responsible and, in doing so, will help in determining the reasons why the spoilage occurred. The next section looks at causes of spoilage in thermally processed foods.

## 13.2 CAUSES OF SPOILAGE

In the context of HACCP, microorganism contamination of a food product can occur in several ways. Although HACCP is intended for food safety assessment, the thought process is helpful in determining the causes of spoilage. For the purposes of studying why spoilage occurred in a thermally processed food, the following classification for microbiological contamination is useful:

- Presence or *growth* of organisms already in the product. This is unlikely for a thermally processed food, unless it by-passes the process altogether.
- *Introduction* of organisms after the thermal process. This is usually during the cooling operation through permanent or temporary holes in the packaging.
- *Survival* of organisms through the process. This requires either an under-process or organisms of high heat resistance to be present.

Spoilage of a thermally processed food is usually caused in one of two ways; first by the growth of microorganisms following leakage or second by under-processing. Other causes are incipient spoilage, gross spoilage and spoilage from thermophilic organisms. Incipient spoilage occurs before the containers enter the retort process and usually results in food that has spoiled but with no surviving organisms to detect. Gross spoilage is caused by major damage to the container and usually results in mixed microflora. Thermophilic spoilage usually occurs with inadequate cooling but can also occur if raw materials become contaminated with heat resistant microorganisms.

When a container of a spoiled food has no viable microorganisms, spoilage may have occurred before the thermal processing step (incipient) or the microorganisms causing spoilage may have died during storage. The latter is known as auto-sterilisation and makes determination of the causes of spoilage difficult.

### **13.2.1 Leaker spoilage**

The most common cause of spoilage, leaker spoilage, requires three factors to be present in order for this to occur. These are:

- (i) holes in the container that can be temporary or permanent;
- (ii) bacteria or organisms present around the holes; and
- (iii) water for their transport.

A pressure gradient between outside and inside of the container is ideal to assist in the movement of organisms. The differential pressure between the headspace of a steam-closed metal can and the outside provides the perfect driving force to assist with drawing liquid from around the can seams into the can headspace. This driving force is less pronounced for flexible packages such as retortable pouches, although capillary action presents a means for bacteria to travel along seal wrinkles.

Leaker spoilage is reported to be the most common type of spoilage, as can be seen from the data in Table 13.1 (Segner, 1979). This data is for metal cans, but it is expected that this pattern of spoilage is similar for other container types, and although published in 1979 these data are still relevant today. A viable mixed microflora of bacterial rods and cocci is indicative of leakage, although it is not unknown for such leakage to be from single bacteria (see Boxes 13.1 and 13.2).

**Table 13.1** Causes of canned food spoilage (taken from Segner, 1979).

Product category	Incipient	Gross	Leaker	Thermophilic	Insufficient process
Vegetables	9	17	255	84	107
Meats	21	3	130	13	31
Poultry	7	2	62	3	22
Soups	1	0	29	3	15
Pasta	1	1	23	11	13
Dairy based	0	0	82	5	8
Petfoods	16	2	154	55	58
Total	55	25	735	174	254
% of all spoiled lots	4	2	60	14	20

**Box 13.1** Example of leaker spoilage: *Staphylococcus aureus* in canned peas (1957, UK)

This was a landmark spoilage incident because it highlighted the need to avoid handling metal cans while they were still warm and wet. Details of the incident are given below:

- A10 cans of peas processed in vertical steam retorts, cooled in a cooling canal with typically 1–2 ppm free chlorine.
- 11 outbreaks, with infected cans largely edible and unblown.
- Poor seams identified with 10% failure in pressure tests and 2–3% ‘blowers’ from production.
- Cans left to dry in baskets for varying times, then unloaded by hand while sometimes wet, and later packed into cartons.
- 9 of 17 handlers were *S. aureus* carriers, one lady with boils matched phage type and she unloaded cans from retort basket at time of outbreak.
- Normal fitness for work restrictions were ignored.

### 13.2.2 Underprocessing

The second most common cause of spoilage is under-processing (see Box 13.3), also referred to as an insufficient process, and this can be caused by several events, for example:

- retort operations that are faulty because of inaccurate or improperly functioning thermometers, gauges or controls;
- excessive contamination of the product for which normally adequate processes are insufficient;

**Box 13.2** Example of leaker spoilage: *Salmonella typhi* in canned corned beef (1964, Aberdeen, Scotland)

This incident highlights the importance of using good quality water for cooling processed cans. Can seams are vulnerable to leaks when hot and the metal is expanded in the seam. Details of the incident are given below:

- 6lb catering cans of corned beef produced in Argentina.
- More than 500 people were diagnosed with typhoid, although only three elderly or already very sick patients died.
- No gas production or product breakdown.
- A meat slicing machine transferred the *Salmonella* onto other meats and the retail counters nearby, so spreading the infection.
- A chlorination plant had been introduced following 3 previous (less publicised) outbreaks in UK, but was out of action.
- Cans were cooled in unchlorinated river water, because the factory cooling wells had collapsed.
- Canning plant was downstream from town sewage outflow, with typhoid endemic in the local population.

**Box 13.3** Example of under-processing: *Clostridium botulinum* in canned vichyssoise soup (1971, USA)

This incident illustrates the importance of controlling and monitoring viscosity of liquids and semi-solids. These rely on convection currents to enhance the heat transfer. Details of the incident are given below:

- A New York man died and his wife had become seriously ill due to botulism after eating a can of vichyssoise soup.
- Five cans of soup were found to be contaminated with the botulism toxin.
- The factory had introduced an improved 'thicker' formulation. They checked with US National Canners Association (NCA) for process times and temperatures, but failed to mention the change in soup viscosity.
- *C. botulinum* spores survived the inadequate process and were able to germinate and grow during ambient storage of the soup.
- Vichyssoise is eaten cold so the botulism toxin could not be destroyed by heating the soup.
- HACCP systems for low acid canned foods were introduced in 1973 in USA as a result of this incident.
- Soup viscosity should be a CCP.

- changes in formulation or handling of the product that result in a more viscous product or tighter packing in the container, with consequent lengthening of the heat penetration time;
- accidental by-passing of the retort operation altogether.

Often with batches of containers that have undergone an insufficient process the level of heat applied to the food will knock out most of the microorganisms leaving a single more heat resistant species. This is usually a spore-forming bacterium from the Clostridia or Bacilli groups.

### 13.2.3 Thermophilic spoilage

This is most commonly associated with inadequate cooling of processed containers in which spores of thermophilic organisms have time to germinate and grow. The time required at ideal growth temperatures for spore germination requires several hours with the food held at 45 to 60°C. Hence, the major cause of thermophilic spoilage is when the cooling cycle of a batch retort is interrupted and the food containers remain in warm water while a retort fault is repaired. Thermophilic spoilage usually results in a single organism isolated from the processed food.

One such fault that is increasing in occurrence is with automatic loading systems that on occasion break down and cause a bank of retorts to stop at varying places in their cycles. In this instance, cooling is not always considered of concern, because the food safety organisms (e.g. *C. botulinum*) will be removed by this stage, leaving only the very heat resistant organisms that are not a safety hazard. Note that thermophilic organisms are not known to cause food poisoning. However, spoilage from these organisms represents considerable commercial damage to companies because of the costs of recalls, compensation and damage to their reputation.

The other common cause of thermophilic spoilage is when raw materials are contaminated with heat resistant microorganisms, either when raw materials suppliers are changed or from batch to batch microflora changes. Chapters 1 and 3 give examples of organisms of high heat resistance, for example *Geobacillus stearothermophilus* and *Clostridium sporogenes*, together with process calculations that illustrate what process levels are required to ensure their adequate destruction. Log reductions of 3 to 5 are used to reduce the numbers of these spores to commercially acceptable levels.

Foods with a simple formulation can sometimes be given a process close to the minimum botulinum cook of  $F_0 3$ , for example beetroot and other vegetables in which texture can be damaged by

higher process levels. This process level will only achieve around 1 to 2 log reductions with most thermophilic organisms and so contamination levels must be minimised. However, formulated foods such as soups and sauces usually contain many ingredients, with certain ones known for being contaminated with heat resistant microorganisms. Starches, herbs and spices have a reputation for containing high numbers of thermophilic spore-forming organisms (see Box 13.4). A process sufficient to achieve 3 to 5 log reductions of these would require  $F_0$  12 to 20, depending on the organism and its level of heat resistance.

### 13.3 DESCRIPTIVE TERMS FOR CANNED FOOD SPOILAGE

Much of the published work on incubation and spoilage of thermally processed foods refers to canned foods. This is because there is a 150-year history in which considerable expertise has been developed over this time period as key spoilage incidents have occurred (see incidents highlighted in the above sections). Information on pouches and plastic trays is less available, primarily because of the

#### **Box 13.4** Example of thermophilic spoilage: *Bacillus sporothermodurans* in retorted rice

Thermophilic spoilage incidents do not often make headline news and so information on specific incidents tends to remain confidential. This example was found in retorted pouches of rice. Some details of the incident are given below:

- Isolated cases of pink spots in rice with mushrooms identified.
- Rice pouches retorted to  $F_0$  6–8 end of heating, and  $F_0$  9–11 end of cooling.
- *B. sporothermodurans* identified as the responsible organism, and introduced from the mushrooms.
- Heat resistance showed it to display thermophilic tendencies, with  $D_{121.1}$  of 2.8 min. Only 5 log reductions achieved during process.
- Initial spore loading per packs were around  $10^5$ , so process was borderline for survival.
- Alternative source of mushrooms sourced, using canned mushrooms with low/zero initial loading.



reduced time period that these containers have been available. Table 13.2 presents some descriptive terms for cans that are useful in understanding the nature of canned food spoilage. They describe incremental increases in gas pressure within the can:

- *Flat*: A can with both ends concave, and they remain in this condition even when the can is brought down sharply on its end on a solid, flat surface.
- *Flipper*: A can that normally appears flat, but when brought down sharply on its end on a flat surface, one end flips out. When pressure is applied to this end, it flips in again and the can appears flat.
- *Springer*: A can with one end permanently bulged. When sufficient pressure is applied to this end, it will flip in, but the other end will flip out.
- *Soft swell*: A can bulged at both ends, but not so tightly that the ends cannot be pushed in somewhat with thumb pressure.
- *Hard swell*: A can bulged at both ends, and so tightly that no indentation can be made with thumb pressure. A hard swell will generally 'buckle' before the can bursts. Bursting usually occurs at the double seam over the side seam lap, or in the middle of the side seam.

The terminology has evolved from the canning sector and unfortunately cannot be easily transferred to other packaging types such as semi-rigid containers and glass. The following tables use these descriptions.

## 13.4 METHODS FOR INCUBATION TESTING

### 13.4.1 Sample size

It is essential that the number of containers examined bacteriologically should be large enough to give reliable results. The exact number of containers for incubation depends on the suspected number of failures, which presumes some prior knowledge of the pack integrity. Sample size can be calculated using statistical procedures (BSI, 1999). Table 13.2 presents the required sample size in order to be 95% sure of finding a defective container (Campden BRI, 2001). The sample size is dependent on the level of contamination (or defective containers) and not on the batch size. These sampling plans were published in BS 6001-1: 1999.

**Table 13.2** Required sample size to be 95% sure of finding a defective container.

Detection level	Number of containers to test
1 in 100	300
1 in 500	1500
1 in 1000	3000
1 in 10 000	30 000

If no defective containers are found during the incubation test, it can be assumed there is a 95% chance that the batch is totally clear of defective containers. This is an unsatisfactory result because the absence of defective containers does not necessarily imply that the batch is sound. This absence of evidence scenario is one of the reasons put forward by some companies for minimising the incubation testing done as routine practice.

If the incubation is carried out as part of a spoilage investigation and the containers for incubation are all known to be spoiled, then the required sample numbers are reduced. This assumes that each of the spoiled containers already contains high numbers of organisms. When the cause of spoilage is clear-cut, incubating 4 to 6 containers may be adequate, but in some cases it may be necessary to incubate 10 to 50 containers before the cause of spoilage can be determined.

### 13.4.2 Temperatures and times for incubation

The exact temperatures and times for incubation testing will depend on the types of microorganisms that will grow. For example, if a low acid food such as beans in tomato sauce is suspected of being under-processed, then incubation at 37°C would be appropriate. Table 13.3 shows some recommended temperatures and times. The general rules for incubation temperatures are 25°C for yeast and mould, 37°C for mesophilic organisms and 55°C for thermophilic organisms.

Control of temperature in an incubator needs to be within  $\pm 1^\circ\text{C}$ , otherwise there could be various types of microorganism growing in the food. Heat transfer from the incubator air to the food containers will be poor, unless a circulation fan is used and the containers are stored on a mesh racking system. It is important that an incubator has a permanent record of the air temperature.

As shown in Table 13.3, the different types of microorganism require incubation at different times and temperatures. These

**Table 13.3** Recommended temperatures and times for incubation testing (taken from Campden BRI Guideline No. 34, Campden BRI, 2001).

Incubation temperature (°C)	Incubation time (days)	Food group and target organisms
25	14	Medium/high acid, targeting acid-tolerant bacteria, yeasts and moulds
30	14	Low acid foods, targeting leaker spoilage with mixed flora
37	10	Low acid foods, targeting under-sterilisation and less optimally leakers
55	7	Low acid foods, targeting thermophiles

conditions are guidelines only and it is likely that specific laboratories will use local variations that are preferred. This is because microorganisms are notoriously hard to categorise and can evolve their growth characteristics to suit their environment.

13.4.2.1 *Thermophilic organisms*

Thermophilic organisms tend to grow between 45 and 65°C although some, such as *Bacillus coagulans*, can grow slowly below 40°C but more optimally at 45°C. Therefore, it is essential to know what organism is expected to grow, so the conditions can be tailored for that organism. Incubation times of 5 to 14 days are required but some organisms, such as *G. stearothermophilus*, can grow and die off within 7 days. This is known as autosterilisation. Regular examination of the containers is essential to ensure the examination is done while the organisms are growing actively.

A further complication for thermophilic growth is the slow increase in food temperature from ambient (5–25°C) to incubation temperature (45–55°C). With high incubation temperatures, large food containers that heat up slowly, and poor heat transfer within incubators, it is necessary to ensure containers are separated in the incubator to maximise heating. If not, mesophilic organisms could start growing while temperatures in the containers are in the 25 to 45°C range, which would confuse the situation.

Incubation testing for thermophilic organisms is essential if thermally processed foods are for export to tropical climates where ambient temperatures regularly exceed 45°C. Process levels must be higher than with foods for sale in temperate climates, so that spores from thermophilic organisms are destroyed.  $F_0$  values of more than 18 to 20 are typically used.

#### 13.4.2.2 *Mesophilic organisms*

Spore-forming mesophilic bacteria prefer growing between 30 and 37°C and so incubation times of up to 21 days are used. A lower incubation time of 10 days is recommended with the higher temperature of 37°C. This tends to be the optimum growth temperature (37°C) for many pathogenic bacteria, although a number of these (including *Salmonella*, *Escherichia coli* and *Listeria*) do not produce spores.

Many non-spore forming mesophilic bacteria are implicated in spoilage from containers that by-pass of the retort or through post-process leaker contamination. Incubation conditions of 14 days at 30°C or 21 days at 25°C are used, with the choice depending on the suspected organism. Mixed flora can be found in either scenario.

Yeast and mould spoilage can also be caused by containers by-passing the retort but is more commonly associated with post-process recontamination. Unless the mould is heat resistant, such as *Neosartorya* spp. or *Byssoschlamys* spp., incubation temperatures should be below 30°C. A minimum incubation time of 14 days at 25°C is recommended; however, the product pH and water activity will be instrumental in determining the precise conditions to optimise growth of the surviving yeast or mould.

#### 13.4.3 **Post incubation inspection of containers**

One of the objectives of incubating food containers is to encourage the surviving organisms to grow under the ideal incubation conditions and reach high numbers so they can be identified by microbiological examination. Information on the methods for identification is given in reference sources such as Campden BRI Technical Manual No.18 (1987) and the FDA Bacteriological Analytical Manual (2001).

Further physical checks on the food after incubation involve pH measurement to identify if the pH has changed as a result of metabolic products of microorganism growth, and loss of vacuum caused by gas generation.

## 13.5 BIOTESTING

Biotesting is a specific type of incubation test that is designed to evaluate new container formats for which little data exists on the seam or seal quality (Campden BRI, 1992). It involves the testing of high numbers of containers and also requires significant populations of microorganisms. As such, it is a test that can only be carried out by specialist laboratories.

A typical biotest involves filling containers with a nutrient material and applying a standard heat process to all of the containers. Sometimes a proportion of the containers will be deliberately damaged in a controlled manner in order to create a defect. These containers will be the positive control. Once the heat process is finished, the containers are cooled in water into which a gas-producing organism such as *Erwinia herbicola* has been added. All of the cooled containers are then incubated at 30°C, or the appropriate temperature for the organism used, and inspected on a daily basis.

## References

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# 14 Critical Factors in Thermal Processing

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## 14.1 BACKGROUND

The HACCP (Hazard Analysis Critical Control Points) system, which is science-based and systematic, identifies specific hazards and measures for their control, to ensure the safety of food. HACCP is a tool to assess hazards and establish control systems that focus on prevention rather than relying mainly on end-product testing. (Codex Alimentarius, 2003). Food Processors should control food hazards through the use of systems such as HACCP.

This chapter does not attempt to cover all of the implementation of a HACCP system for thermal processing, rather it discusses various critical factors to assist in the identification of Critical Control Points (CCPs). Food processors should:

- **identify** any steps in their operations that are critical to the safety of food;
- **implement** effective control procedures at those steps;
- **monitor** control procedures to ensure their continuing effectiveness;
- **review** control procedures periodically, and whenever the operations change.

Hygiene control systems should be applied throughout the food chain to control food hygiene throughout the shelf-life of the product through proper product and process design. Control procedures may be simple, such as checking stock rotation or calibrating equipment. In some cases, a system based on expert advice, and involving documentation, may be appropriate.

## **14.2 KEY ASPECTS OF HYGIENE CONTROL SYSTEMS FOR FOOD PROCESSING (FROM CODEX ALIMENTARIUS)**

Inadequate food temperature control is one of the most common causes of food-borne illness or food spoilage. Such controls include time and temperature of cooking, cooling, processing and storage. Systems should be in place to ensure that temperature is controlled effectively where it is critical to the safety and suitability of food. Temperature control systems should take into account:

- the nature of the food, e.g. its water activity, pH and likely initial level and types of microorganisms;
- the required shelf-life of the product;
- the method of packaging and processing;
- the end use of the product.

Such systems should also specify tolerable limits for time and temperature variations. Temperature recording devices should be checked at regular intervals and tested for accuracy.

Examples of other steps that contribute to food hygiene and safety include:

- chilling;
- thermal processing;
- irradiation;
- drying;
- chemical preservation;
- vacuum or modified atmospheric packaging.

Each of these steps can be considered as processing methods (Chapter 7), but are discussed in detail as microbiological hurdles in Chapter 2.

Contamination of food can occur via biological, chemical or physical sources. This book deals primarily with contamination by microbiological means; however, it is essential that chemical and physical contamination is understood so that it can be controlled within the thermal processing environment.

Transfer of microorganisms to the food product, processing equipment or to packaging needs consideration at various stages of the processing lines. Pathogens can be transferred from one food to another, either by direct contact or by food handlers, onto contact surfaces or through the air. Raw, unprocessed food should

be effectively separated, either physically or by time, from processed food. Access to processing areas should be restricted or controlled. These are good manufacturing practices and are usually handled as one of the prerequisites in the HACCP plan of a company.

Systems should also be in place to prevent contamination of foods by foreign bodies such as glass or metal shards from machinery, dust, harmful fumes and unwanted chemicals. In manufacturing and processing, suitable detection or screening devices should be used where necessary.

No raw material or ingredient should be accepted by a food processor if it is known to contain parasites, undesirable microorganisms, pesticides, veterinary drugs or toxic, decomposed or extraneous substances that would not be reduced to an acceptable level by normal sorting and/or processing. Specifications for raw materials should be identified and applied and raw materials or ingredients should be inspected and sorted before processing.

One of the functions of the packaging of a heat preserved food is to provide adequate protection for products to minimise re-contamination after processing. It is imperative that packaging materials are non-toxic and do not pose a threat to the safety and suitability of food under the specified conditions of processing, storage and use. This includes changes to the packaging materials as a result of the applied heat process, and should also consider the material breakdown that could arise from flexing of containers during the process.

Water quality is important. Only potable water should be used in food handling and processing, with the following exceptions: for steam production, fire control and other similar purposes not connected with food. Water recirculated for reuse should be treated and maintained in such a condition that no risk to the safety and suitability of food results from its use.

### **14.3 IDENTIFYING CRITICAL CONTROL POINTS IN THERMAL PROCESSING**

An in-depth understanding of the product being processed is vital to be able to identify critical factors and set up critical control points and measurements. Critical factors of thermal processing are physical and chemical factors that can influence the thermal response of a product to the thermal process, the variation of which may influence the scheduled process, including container, product, retort and processing conditions (ITFPS, 1995; FDA Guidelines).



Critical factors that relate to the product characteristics are numerous and include the following:

### **14.3.1 Microbial load or bio-burden**

The way that microorganisms are killed by wet heat will be considered in many of the chapters of this book. It is clear that the starting number of microorganisms will have a direct influence on the final number of microorganisms given the same process. It follows that if a product or ingredient is unusually contaminated, the risk of surviving viable cells or spores will be higher.

### **14.3.2 pH of the product**

The term 'pH' is used to designate the intensity or degree of acidity of the product. It is an intrinsic characteristic of the product, although factors such as ripeness in fruit or rigor mortis in meat or simply variety can show small but significant variations in the pH. The value of pH, the logarithm of the reciprocal of the hydrogen ion concentration in solution, is determined by measuring the difference in potential between two electrodes immersed in a sample solution. This is discussed in greater detail in Chapters 4 and 5.

As has been discussed, low acid foods have a pH of greater than 4.6 and acid or acidified foods have a pH of less than or equal to 4.6 (Table 14.1). The pH of the product immediately after processing is considered to be the significant pH.

The kinds of microorganisms that can grow and survive in heat treated foods are strongly dependant on the pH of the food. While strict control of pH is critical for acid and acidified foods, especially around the range of 4.0 to 4.8, as pH is generally one of the two hurdles that keep these products safe and stable, it is also important for low acid foods. The Thermal Death Time (TDT) of most microorganisms is closely linked to the pH of the medium or food. The efficacy of the thermal process is linked to its pH, and this should not be allowed to vary significantly. More than 0.2 pH units are considered to be significant for most products.

### **14.3.3 Water activity ( $a_w$ )**

Water activity is a measure of the amount of water that is available to support microbial growth. It is one of the hurdles to the growth and survival of microorganisms (Table 14.2). Changes in water activity can affect the efficacy of the thermal process and hence

**Table 14.1** Examples of common variation in the pH of some fresh fruit.

<b>Fruit</b>	<b>Min pH</b>	<b>Max pH</b>
Pears	3.6	4.7
Cherries	3.6	4.4
Tomatoes	3.9	4.7

**Table 14.2** Minimum water activity required for growth (taken from Mossell and Ingram, 1955).

<b>Organism</b>	<b>Minimum <math>a_w</math></b>
Normal bacteria	0.91
Normal yeasts	0.88
Normal moulds	0.80
Halophilic bacteria	0.75
Xerophilic fungi	0.65
Osmophilic yeasts	0.60

the risk of survival of spoilage microorganisms or microorganisms of public health significance. Lower water activity reduces the ability of microorganisms to take up nutrients and compounds for metabolism.

Salt and sugar are both examples of compounds that can be added to reduce water activity; salt in cured meats, sugar in jam.

#### 14.3.4 Consistency

The consistency or viscosity of the product has a direct relationship with the rate of heat transfer into the product. In foods, heat transfer can be by two mechanisms; conduction or convection, and the consistency of the food determines which is dominant. Corned beef, for example, is a solid pack that heats slowly by conduction, whereas peas in brine heat rapidly by convection. Not all heating is either conduction or convection, as there are combinations of the two that are determined by-product characteristics. The viscosity of the sauce, and the amount, size and shape of solid particles all affect the heating patterns. These factors are considered in some detail in Chapter 9 on Measurement and validation of thermal processes.

The formulation is fundamental to the physical characteristics of the product. Any changes or deviations from what is standard will affect the rate of heating and hence could affect the safety of the thermal process. Besides the consistency of the product, which includes the viscosity, the solid ingredients are also critical to the characteristics of the product.

#### 14.3.5 Presence, concentration and types of preservatives

In some products, chemical preservatives are used in the product formulation, either for flavour or to enhance the efficacy of the thermal process or for both.

**Cured meats** have sodium and potassium salts such as chloride, nitrite and nitrate, as well as sometimes polyphosphates and ascorbate that give the products their characteristic flavour and appearance, but also have a preserving action so that a sub  $F_0 3$  thermal process is sufficient. The preserving action of salt is primarily due to the lowering of the water activity.

Unfortunately, not all microorganisms are susceptible to the action of nitrite, but of those that are (e.g. anaerobic spore-formers such as *Clostridium botulinum*) nitrites are taken up into the cell and inhibit the ability to form energy rich compounds and therefore inhibit growth and cell division. Nitrites are effective particularly at acidic pH, specifically less than pH 6.0 (Rahman, 2007). Nitrates do not have any direct action, but are converted into nitrites, which inhibit growth.

Typically cured luncheon meats contain 3.0 to 4.0 % NaCl (salt on water phase) and 150ppm (0.015%) nitrite, and are given a thermal process equivalent to  $F_0$  1.0 to 1.5.

#### 14.3.6 Rehydration

Heat transfer in dry material will be slower than in moist, so dehydrated ingredients must be thoroughly and consistently rehydrated. Dried ingredients cannot be substituted for fresh without the appropriate testing.

It is important to understand that the storage conditions, such as time, temperature and humidity, of dry ingredients can affect the way that they rehydrate. Rehydration of solids must be done in a known controlled fashion. If the cooking process has to rehydrate ingredients, any changes to these procedures (e.g. higher temperature, shorter time) may cause inadequate hydration.

It is often found that dried materials have higher levels of microbial contamination than fresh, and therefore achieving complete rehydration before the thermal process killing step is critical.

### **14.3.7 Blanching**

Blanching is used in the preparation of raw materials for many products. It is a short heat treatment, usually either in steam or in water. The benefits of blanching are many and include:

- wilting of plant tissue to facilitate packing into containers;
- expelling air from plant tissue. Removal of oxygen can improve the colour and extend the shelf-life of the product, as well as changing the density;
- inactivating enzymes, to improve the colour, flavour and nutritional value, as well as preventing enzymatic action before the containers enter the thermal process;
- preheating the product, which affects the vacuum in canned food, as well as reducing the required process time as a result of elevated initial product temperatures;
- reducing the initial microbial load on the product, specifically of vegetative cells.

It is worth noting that over- or under-blanching can affect the container fill weight and the solids to liquids ratio. Both of these are critical factors.

Also of concern with blanching operations is that thermophilic bacteria can grow inside blanchers. To prevent this happening, blanchers should be operated in the 88 to 93°C (190–200°F) range. Maintaining product at or above 82°C (190°F) helps to control thermophilic growth. If blanchers must be operated at temperatures lower than 82°C because of product considerations, then they should be regularly evaluated for thermophilic growth and build-up.

### **14.3.8 Size and style of in-going ingredients**

Larger pieces of solids will take longer to heat at their centre, because the solids will heat by conduction. The thermal process is designed to deliver a process at the coldest spot in the container, which might be in the centre of a solid ingredient. The relationship between particulate size and process time requirements is illustrated by the data in Table 14.3.

**Table 14.3** Recommended process times for various size shrimps in brine in 307×113 cans processed at 250°F (121.1°C) with a minimum initial temperature of 45°F (7.2°C) (taken from NFPA Bulletin 26-L, 1982).

Shrimp size	Minutes at 250°F
Medium, Small, Tiny	14
Large	16
Extra Large, Jumbo	18

**Table 14.4** Recommended process times for asparagus in brine in 211×304 cans processed at 250°F (121°C) with a minimum initial temperature of 70°F (21.1°C) (taken from NFPA Bulletin 26-L, 1982).

Asparagus style	Minutes at 250°F
Cuts	13
Spears, Tips Down	19
Spears, Tips Up	21

The style of the ingredient also can affect the rate of heat penetration. For example, French cut (diagonal) and cross-cut green beans do not have the same rate of heating. Similarly sliced or diced carrots constitute very different packs in terms of their heating rates. Asparagus spears heat up differently if the tips are positioned up compared with the tips pointing down (Table 14.4).

As a general rule, the higher the mass of product the longer it will take to heat, although the physics of conduction heat transfer dictates that the thickness is the critical dimension. Also the higher the mass of the solid components of the product, the longer it will take to heat because of the predominance of conduction heat transfer.

**14.3.9 Container, packing and filling considerations**

**14.3.9.1 Headspace**

The headspace is the closed space containing air or gasses above the food inside a closed container. The size of headspace is critical when forced convection heating is used in agitated retort, especially with end-over-end or axial agitation. This is because the headspace acts as a bubble that travels through the product and

mixes the regions of higher and lower temperature. If the headspace volume is too small, inefficient or no mixing will take place and the rate of heating of the product will be markedly reduced.

Not all of the headspace actions relate to heat transfer. An excessive headspace will result in too much air inside a container and excessive oxygen (~21% of air is oxygen). This can result in oxidation of the product, especially at the headspace product interface and can cause unsightly browning or discolouration. Excessive oxygen can also cause corrosion of the interior of the container.

If the process is static, a large headspace can result in a layer of air that acts as an insulation layer and may reduce heat transfer. This becomes important for containers where the diameter is larger than the height, and so heat transfer occurs primarily through top and bottom surfaces.

A general rule is that the headspace should be about 5% of the container volume.

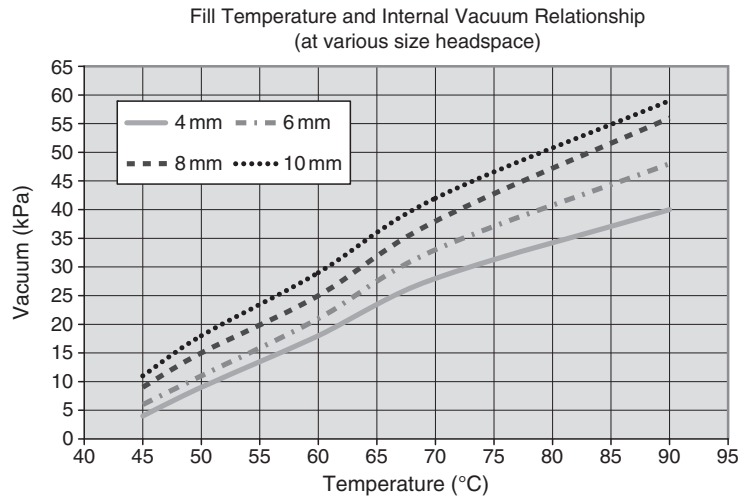
#### 14.3.9.2 *Container vacuum and exhausting of containers*

The vacuum in a container serves as a visual indicator that no gas forming microbiological spoilage has taken place. It also reduces the amount of air (and hence oxygen) inside the container, which reduces the potential for oxidative deterioration of the product and corrosion of the container.

Excessive air inside cans can result in large pressure build-up during processing, which can cause the ends to deform irreversibly (peak) or bulge (flippers). As mentioned above, too much air inside the container can result in a layer of air that can insulate and reduce heat transfer.

Air can be removed from the container and a vacuum formed by several methods:

- *Hot filling*: Filling hot product into the container and sealing it while hot will result in a vacuum being formed as the product cools and contracts. The fill temperature is directly proportional to the final vacuum, but is also influenced by headspace. Figure 14.1 illustrates the relationship between fill temperature and the vacuum formed.
- *Exhaust box*: The product is filled into the container and then is passed through a steam or hot water exhaust box. Usually only for metal cans.
- *Mechanically*: The containers are filled and passed into a chamber, where a vacuum is drawn and the container end is sealed on. Usually only for metal cans.



**Fig. 14.1** Relationship between fill temperature and the vacuum formed, for various headspace volumes. For a colour version of this figure, please see the colour plate section.

- *Steam injection:* Steam is injected into the headspace of the container immediately prior to seaming or fitting the lid. The steam displaces the air in the headspace and forms a vacuum when it condenses.

#### 14.3.9.3 Container size and geometry

The shape and size of the container is very important to the position and the rate of heating of the cold spot in the product. The cold spot in larger containers will take longer to reach the desired temperature or lethality (Table 14.5). In addition, the shape of the container will affect the position of the cold spot. This can be especially problematic for flexible containers, where even slight

**Table 14.5** Recommended process times for baked beans in tomato sauce in various can sizes, processed at 250°F (121.1°C) with a minimum initial temperature of 70°F (21.1°C) (taken from NFPA Bulletin 26-L, 1982).

Can size (US)	Minutes at 250°F
211 × 400	69
307 × 214	80
307 × 400	100
603 × 700	275

**Table 14.6** Recommended process times for cream style corn with various initial temperatures, processed at 240 and 250°F (115.6 and 121.1°C) (taken from NFPA Bulletin 26-L, 1982).

<b>Initial temperature (°F)</b>	<b>Process time at 240°F (minutes)</b>	<b>Process time at 250°F (minutes)</b>
140	70	52
160	67	49
180	62	45

variations in fill volume or headspace can affect the geometry of the container.

#### 14.3.9.4 *Initial temperature of product*

Initial temperature is defined as the average temperature of the contents of the coldest container to be processed at the time that the thermal processing cycle begins. It is determined after thorough shaking or stirring of the filled and sealed container. The initial temperature is a critical control point because it has a direct influence on the time taken for the cold spot in a container to achieve the minimum required temperature or lethality (Table 14.6).

### 14.3.10 **Process related critical factors**

#### 14.3.10.1 *Processing method*

The type of retort (e.g. still, horizontal, vertical or crateless, or agitating) can affect the rate of heat transfer into the cans. If agitation is used, the method of agitation (end-over-end, axial and intermittent) can significantly affect the rate of heating. Batch processes compared with continuous processes can also vary.

#### 14.3.10.2 *Processing medium*

The heating medium (e.g. saturated steam, steam/air mixtures, water immersion, water spray and water cascade) is critical to the rate of heat transfer from the media to the container surface. Air is one of the worst heat transfer media, despite its widespread use in refrigeration and ovens, and prolonged contact with container surfaces will result in poor heat transfer. It is for this reason that venting of retorts is so important to processing, and the agitation or circulation of heating media is critical to the even distribution of heat and also during cooling.



#### 14.3.10.3 *Type and characteristics of heat processing system*

The type of processing system and the way that it operates should be understood and must be reproducible. For example, the method of loading baskets (e.g. crateless, jumble packed, stacked with or without layer pads) must be fixed and consistent between batches. Orientation of the containers (vertical, horizontal or jumble packed) must also be consistent, because different orientations can affect the rate of heat transfer, especially if the packs heat by convection.

For steam retorts, the vent schedule must be established to achieve air removal, and there should be a minimum come-up time specified before the hold time can commence.

The pressure inside the retort must be stable and must correspond to the required pressure for that given temperature and altitude (only for condensing steam retorts). A retort operating at a pressure above the saturated steam pressure could indicate inadequate venting. This is because a mixture of air and steam will have a higher pressure than for saturated steam. This situation is further complicated by variation in atmospheric pressures at different altitudes, as shown in Table 14.7.

#### 14.3.10.4 *Processing temperature*

Operating a retort at the correct processing temperature is vital. The official temperature measuring device for processes filed with the FDA is the mercury-in-glass (MIG) thermometer, which must be annually calibrated and regularly validated. Although this situation is currently changing and thermometers based on platinum resistance principles are now acceptable to the FDA, many companies still rely on the MIG as their master temperature indicator (MTI). It is very important that the MTI, the temperature controller and the recording chart are all set to read the same, as otherwise there is no reliable record of the process. Small deviations in process temperature can result in dramatic changes in the accumulated lethality of a process. This is illustrated with the data in Table 14.8 for canned pilchards in tomato sauce.

Small deviations from the product or processing specification, which may seem negligible or insignificant, may seriously affect the adequacy of the process for that product, therefore any changes or deviations should be evaluated for the effect on the adequacy of the process.

**Table 14.7** Gauge pressure (psi) corresponding to specified process temperature at various altitudes, note that  $\text{psi} \times 6.895 = \text{kPa}$ .

Temp (°F)	Sea level	Feet above sea level							Temp (°C)
		500	1000	2000	3000	4000	5000	6000	
200	–	–	–	–	–	–	–	–	93.3
205	–	–	–	–	–	–	0.5	0.9	96.1
210	–	–	–	0.4	0.9	1.4	1.8	2.3	98.9
212	0.0	0.2	0.5	1.0	1.5	2.0	2.4	2.9	100.0
215	0.9	1.1	1.4	1.9	2.4	2.9	3.3	3.8	101.7
220	2.5	2.7	3.0	3.4	3.9	4.4	4.9	5.3	104.4
225	4.2	4.5	4.7	5.2	5.7	6.2	6.6	7.1	107.2
230	6.1	6.3	6.6	7.1	7.6	8.0	8.5	9.0	110.0
235	8.1	8.3	8.6	9.1	9.6	10.0	10.5	11.0	112.8
240	10.3	10.5	10.8	11.3	11.7	12.2	12.7	13.1	115.6
242	11.2	11.4	11.7	12.2	12.7	13.1	13.6	14.1	116.7
245	12.6	12.9	13.1	13.6	14.1	14.6	15.0	15.5	118.3
248	14.1	14.3	14.6	15.1	15.6	16.0	16.5	17.0	120.0
250	15.1	15.4	15.6	16.1	16.6	17.1	17.5	18.0	121.1
252	16.2	16.4	16.7	17.2	17.7	18.1	18.6	19.1	122.2
255	17.8	18.1	18.3	18.8	19.3	19.8	20.2	20.7	123.9
260	20.7	21.0	21.2	21.7	22.2	22.7	23.1	23.6	126.7
265	23.8	24.0	24.3	24.8	25.3	25.8	26.3	26.8	129.4
270	27.3	27.5	27.8	28.3	28.8	29.3	29.8	30.3	132.2
275	30.9	31.2	31.5	32.0	32.5	33.0	33.5	34.0	123.0

**Table 14.8** Accumulated process lethality for pilchards in tomato sauce in 73 × 110 mm cans, at various process temperatures with initial temperature of 60°C.

Process temperature (°C)	F <sub>0</sub> achieved at 75 minutes (minutes)	Process time to achieve F <sub>0</sub> 6 (minutes)
116	5.4	78
118	7.7	71
121	12.9	62

#### 14.3.10.5 Processing time

The process time is also critical to the safety of a thermal process. It is important, when using automatic timing devices linked to the retort controller, to ensure that if there is a temperature over-shoot,

**Table 14.9** Lethality increase ( $F_0$ ) per minute of process time at various temperatures.

Can centre temperature (°C)	Increase in $F_0$ per minute (minutes)	Can centre temperature (°C)	Increase in $F_0$ per minute (minutes)
111	0.10	121	0.98
112	0.12	122	1.23
113	0.15	123	1.55
114	0.19	124	1.95
115	0.25	125	2.45
116	0.31	126	3.09
117	0.39	127	3.89
118	0.49	128	4.90
119	0.62	129	6.17
120	0.78	130	7.76

and then an automatic correction, that the timer only starts once the temperature has stabilised at the process temperature. Table 14.9 presents data for the increase in  $F_0$  per minute for container centre temperatures between 111 and 130°C. This illustrates the importance of correct timing for process hold periods.

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## 15 Environmental Aspects of Thermal Processing

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Environmental concerns are driving business and policy changes in both Europe and many parts of the world (Stern, 2006). Global warming, also referred to as climate change, is the principal environmental issue of concern because of its effects on changing climates for growing food globally. It is increasingly accepted that the change in climate over the last 100 years is due to an increase in atmospheric concentrations of greenhouse gases (GHG) and that anthropogenic sources are playing a major role in these increases. Implications for agricultural systems in most growing regions of the world are substantial.

A key commercial driver for businesses to reduce GHG emissions is the growing need to satisfy customer demand for products from 'sustainable sources'. This is leading businesses to consider the other environmental and social impacts of their activities, in addition to global warming potential. Large food producers and retailers are undertaking lifecycle assessments (LCA) that cover a range of environmental impacts for the lifecycle of their products. This requires a study of all stages in the production of a unit of food and includes production of raw materials, the manufacturing process, transport and distribution, retail, consumer use and waste disposal. In a food context, this includes farming activities, packing, transport to market, retail, in-home preparation and consumption, and waste disposal at all stages of the lifecycle.

In addition to business drivers, there are policy and legislative drivers for decreased greenhouse gas emissions and sustainable development (IPCC, 1997, 2006). For example, the new UK Climate Change Bill has set a target for an emissions decrease of 80% by 2050. At an EU level, the European Commission has a policy called Integrated Product Policy (IPP), which promotes sustainable development through:

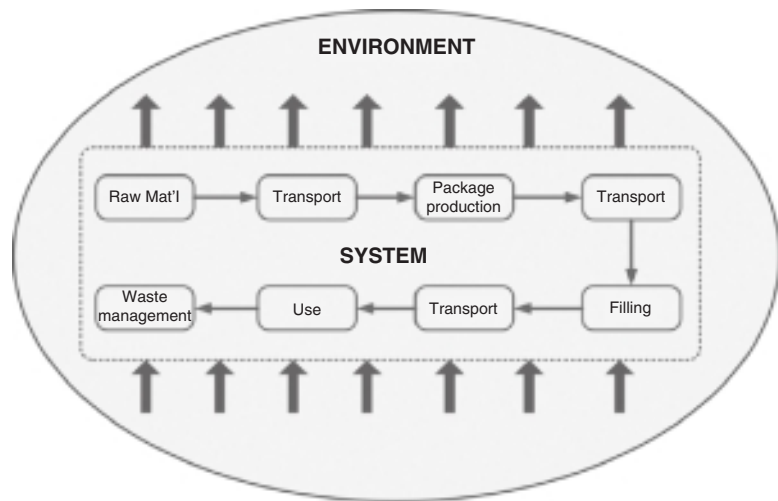
- lifecycle thinking;
- working with the market (to reward companies that are innovative, forward-thinking and committed to sustainable development);
- continuous improvement (IPP requires producers to constantly look for potential improvements);
- stakeholder involvement;
- a mix of instruments (includes economic instruments, substance bans, voluntary agreements, environmental labelling and product design guidelines).

Assessing the GHG emissions arising from the manufacture of a food product has recently been the subject of a UK initiative that resulted in a new publication referred to as PAS 2050 (Publicly Available Specification for the assessment of the lifecycle greenhouse gas emissions of goods and services). This document, recently published by the British Standards Institution (BSI) is based on existing internationally accepted standards (ISO 14044:2006 and ISO 14040:2006) and is under consideration as a seed document for a new international standard (PAS 2050, 2007).

Thermal processing, as a technology for preserving food, can be environmentally beneficial because the goods are stored ambient (avoiding the need for refrigeration) and agricultural products are processed close to where they are grown (avoiding transportation emissions and forcing crops to grow out of season). An example of a GHG assessment is given in this chapter for a bottled apple juice.

## 15.1 LIFECYCLE ASSESSMENT (LCA)

LCA was developed to study the environmental impacts arising from the production, use and disposal of products or services. These do not necessarily have to be foodstuffs. LCA provides a mechanism for investigating and evaluating such impacts all the way from the extraction of basic materials from Nature, from production through packing, distribution, retail, product use (e.g. home cooking and consumption of food) and end-of-life management (e.g. disposal of waste from peeling fruit). LCA considers the environmental impact of the 'product systems' in terms of the environmental consequences of flows (principally flows of substances) between such systems and the environment (Fig. 15.1).



**Fig. 15.1** Product systems and the environment (courtesy of Chris Foster).

In conducting an LCA on a specified product system, all inputs to the system are ideally traced back to primary resources. For example, the impacts of electricity generation are not only those of power station operation and electricity transmission, but include extraction of primary fuels such as coal, oil and uranium and the burdens of refining. All outputs from the system are ideally followed forward through subsequent processing until they enter the environment. LCA considers impacts on all environmental media – air, water and land.

The LCA process has become standardised. The ISO 14040 series contains the main standards applicable to LCA. ISO 14040 (2006) describes the four main elements of an LCA study as being:

- (i) goal definition and scoping;
- (ii) lifecycle inventory development (compiling the inventory of relevant inputs and outputs);
- (iii) lifecycle impact assessment (LCIA) (evaluating the potential impacts associated with the inputs and outputs identified in the lifecycle inventory);
- (iv) improvement analysis (interpreting the results in relation to the objectives).

### 15.1.1 Impact categories

LCA assesses a number of environmental impact categories. The main categories that are relevant to the agri-food sector, and specifically thermal processing, are as follows.

#### 15.1.1.1 *Global warming potential (GWP)*

A global warming potential assessment is sometimes referred to as a carbon footprint. Lifecycle emissions of greenhouse gases are assessed and expressed in units of carbon dioxide equivalents ( $\text{CO}_2\text{e}$ ), calculated by multiplying the mass of a given greenhouse gas by its global warming potential. This is the method described in PAS 2050 (Tucker *et al.*, 2008).

Thermal processes are in general low in GHG emissions because foods are heated and cooled efficiently, are stored in ambient conditions (non-refrigerated), and the raw materials can be processed close to the growing regions. The relative GHG efficiency of a thermal process will be highlighted in the bottled apple juice example.

#### 15.1.1.2 *Pesticide use/ecotoxicity*

Impact assessment of ecotoxicity in LCA is complicated by the fact that not all toxic chemicals have the same mechanism of action (whereas all greenhouse gases do). There is also a large (and to some extent evolving) number of substances that can contribute to the impact category, ranging from metals, through persistent organic pollutants to pesticides. The most commonly used methods relate relevant releases to a reference substance (e.g. 1,4-dichlorobenzene) by means of calculated toxic equivalency potentials, and one of these may be used in this instance.

Thermal processing is no different to other means of food preservation in that the crops and raw materials are grown using standard agricultural practices, which includes pesticide use.

#### 15.1.1.3 *Abiotic resource use*

This captures the extent to which the activities in the product's lifecycle contribute to the depletion of non-living resources – essentially fossil and mineral resources. Several assessment methods are available, since the 'environmental impact' of mineral or fossil resource use is somewhat difficult to define. The widely-used CML (Centre for Environmental Sciences, Leiden University) method relates all abiotic resource use to extraction of a single substance (antimony) on the basis of the relative abundance of different resources. The eco-indicator' 99 method takes a different approach, assessing the significance of resource consumption now in terms of anticipated additional energy demand extraction of the same resource at a designated point in the future. The latter method considers fossil energy use and mineral use

separately – something of an advantage given the high profile of fossil fuel consumption.

Thermal processing can be an attractive preservation method in terms of its minimal depletion of abiotic resources for certain packaging materials, when compared with other technologies. For example, metal and glass packaging both require high quantities of energy for their extraction (and so are relatively high in their GWP), but have a minimal effect on the abiotic resources of the planet. After oxygen and silicon, aluminium is the third most common element and the iron fourth, and both metals can be recycled infinitely without degradation to the metal quality. For example, 54% of steel is recycled in the EU and since 150 years ago, 75% of all primary aluminium is still in use. Glass is extracted from silica sand using limestone and soda ash, which are readily available raw materials. In addition, recycled glass (cullet) can be added in the extraction process up to levels of 81% for green glass, and lightweighting of bottles is now commonplace.

#### 15.1.1.4 *Acidification potential*

Acidification impact assessment quantifies acid-gas releases from the system and/or the subsequent damage they cause. Both mid-point methods (quantifying the burden produced in terms of a single acidic substance – hydrogen ion or sulphur dioxide) and end-point methods (quantifying the actual impact of those burdens on the environment) are available. Using the latter involves assuming some model relating amount of acidic substance deposited to the extent of environmental damage caused (e.g. rate of plant species attrition per unit area per year per kg acid deposited). Acidification was known as acid rain during the 1970s and mainly caused by sulphur and nitrogen oxides released during combustion of coal and oil.

GWP includes emissions during combustion, albeit calculated in a slightly different way, so the above comments on thermal processing having a low impact are relevant also for acidification.

#### 15.1.1.5 *Eutrophication potential*

Eutrophication is quantified in units of phosphate equivalents. Agricultural sources include nitrate ( $\text{NO}_3$ ) and phosphate ( $\text{PO}_4$ ) leaching to water, and ammonia ( $\text{NH}_3$ ) emissions to air. A consequence of phosphate leaching into watercourses is the prevalence of algal blooms in rivers and lakes. These clog up waterways, are



unsightly and deplete oxygen as the algae decompose. In addition, once minerals such as phosphates enter the river systems they become so diluted that it is not possible to recover them economically. Phosphorous is one such element of which there is global concern over the long-term availability of deposits that can be mined.

Thermal processing is no different to other means of food preservation in that the crops and raw materials are grown using standard agricultural practices, which includes fertiliser use. The impact of thermal processing on eutrophication is likely to be neutral and no different to other food preservation methods.

#### 15.1.1.6 *Land use*

Assessing the impacts of land use for all parts of the system is problematic. Land occupancy is recorded by some practitioners for systems in which plant-derived resources play a significant part, as an indicator at least, of the extent to which this finite resource is utilised for the function being considered. The assignment of impacts associated with changes in land use to particular products remains an area in which consensus is still being developed.

It could be argued that thermal processing enables raw materials to be grown in regions that are suited for this purpose and so land use change does not need to be forced. However, this may be a biased argument and thermal processing is best considered neutral in its effects on land use change.

#### 15.1.1.7 *Water use*

No well-established Lifecycle Impact Assessment (LCIA) method exists for the environmental impacts associated with water use. Two obstacles have hindered emergence of an LCIA method relating water consumption to its environmental significance. The first is that the significance of any water consumption is highly location-dependent in terms of its implications for the water resource base; and LCA is a rather location-insensitive method in its current form. The second is that water consumption data is seldom included in LCA datasets in a manner that enables water-resource implications to be established. However, given the extent to which global warming is affecting rainfall patterns, the water use impact category is increasing in importance.

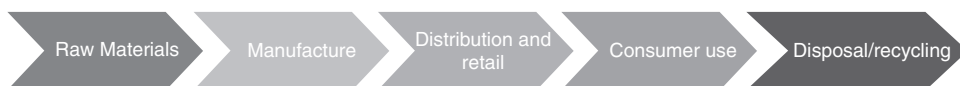
Thermal processing can be applied close to the growing region for a vegetable or fruit product, which allows the crops to be grown

where water supply is guaranteed. Transport of a packaged and shelf stable product is also more economical than for those that are perishable. Thus, thermal processing can help prevent water being taken for agricultural purposes in parts of the world where its scarcity prevents it being used for drinking.

## 15.2 GREENHOUSE GAS EMISSIONS

One of the most important LCA impact factors for today is the effect of an activity on global warming. This is assessed by calculating greenhouse gas (GHG) emissions in terms of their carbon dioxide equivalent values ( $\text{kg CO}_2\text{e}$ ). The terms carbon footprint and GHG emissions have similar meanings and are interchangeable.

To calculate a carbon footprint for the production of a food product or for a food business requires all of the stages involved in that activity to be considered. Figure 15.2 illustrates the linkage between raw materials production through to disposal of the waste and final product at the end of its life. Each stage must be assessed for the GHG emissions using a detailed series of calculations (see Example 15.1).



**Fig. 15.2** Stages required in the GHG assessment of a food product.

### Example 15.1 Beef, a high carbon footprint ingredient

Beef cattle produce large quantities of methane as a result of enteric fermentation. Methane has a GWP of 25 times that of carbon dioxide and so this can lead to cattle products such as beef and milk with high carbon footprint values.

Over-use of nitrogenous fertilisers when growing crops results in the release of nitrous oxide into the atmosphere. This will result in a high carbon footprint for that crop, because nitrous oxide has a GWP of 298 times that of carbon dioxide. To reduce the carbon footprint, the nitrogen-rich fertiliser should be applied at the correct dosing rate and at the correct time to maximise its absorption. Research is being undertaken to farm cattle in conditions that minimise the release of methane.

**Table 15.1** Relative Global Warming Potential (GWP) of the main greenhouse gasses of relevance to the food industry.

Greenhouse gas	Formula	GWP
Carbon dioxide	CO <sub>2</sub>	1
Methane	CH <sub>4</sub>	25
Nitrous oxide	N <sub>2</sub> O	298

Calculation of GHG emissions is carried out relative to carbon dioxide that is given a value of unity (Table 15.1). PAS 2050 contains a more complete table that includes gases used in refrigeration, solvents and packaging. It is apparent from Table 15.1 that a process releasing nitrous oxide has the potential for much greater global warming impact than one releasing carbon dioxide (Wiltshire *et al.*, 2009).

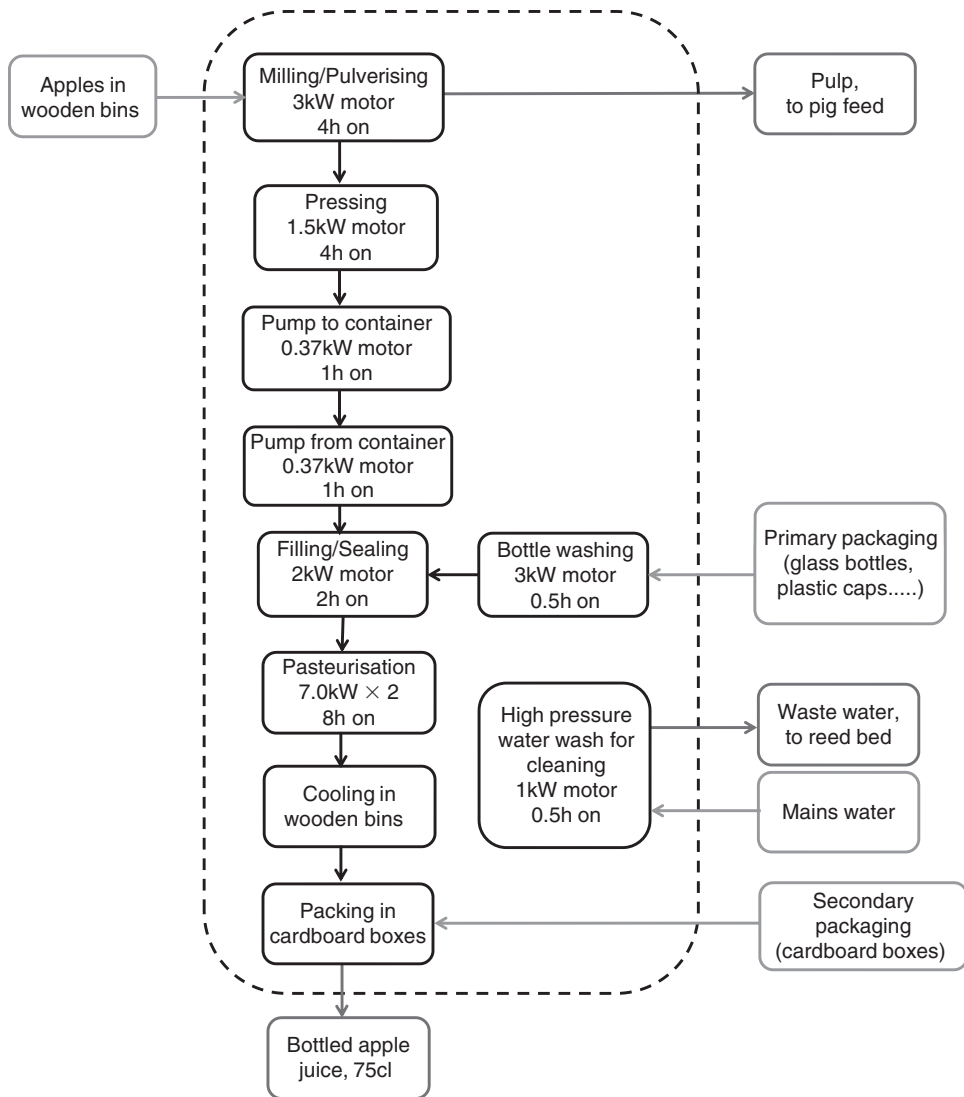
The next section presents a case study for a thermally processed product, bottled apple juice, which demonstrates the methods involved when calculating a carbon footprint value.

15.2.1 Case study: Bottled apple juice

This study estimates the embodied GHG emissions during manufacture of a 75 cL bottle of Cox’s apple juice. The bottled juice is in-pack pasteurised to destroy yeasts and moulds, which requires a process of at least 2 minutes at 70°C. In addition to the primary packaging (glass bottle), the bottles were packaged into cardboard boxes of 12 bottles per box.

The apple juice carbon footprint (CF) includes all material emissions generated as a direct or indirect result of the product unit (PU) being produced. PAS 2050 allows immaterial emissions to be excluded, which are any single sources less than 1% of the total emissions, up to a maximum of 5%. In the apple juice example, ascorbic acid is added in very small quantities to minimise browning of the pressed juice; this is excluded from the calculations.

Figure 15.3 shows an outline flow diagram from the point at which apples are taken into the juicing room, up to when the bottled juice is ready for distribution from the farm. It shows the single raw material input (apples), the various packaging inputs and the two waste streams (pressed pulp and waste water). The juicing operation takes place in a dedicated room, shown with a dotted line.



**Fig. 15.3** Outline flow diagram for bottled apple juice manufacture.

#### 15.2.1.1 Raw materials (0.407kg CO<sub>2</sub>e/PU)

The chosen variety of apple is Cox's Orange Pippin; however, the data calculated for manufacture and packaging of apple juice is not specific to this variety. A CF value for Cox's apples of 0.075 kg CO<sub>2</sub>/kg was used (Wiltshire *et al.*, 2009), based primarily on assessments of fertiliser use and machinery outputs, with apples grown in a modern orchard. Allowing for a 70% juice recovery

**Table 15.2** GHG emissions (kg CO<sub>2</sub>e) for the packaging materials used for 75 cL bottles.

Component	Weight (g/PU)	GHG value (kg CO <sub>2</sub> e/kg)	GHG value (kg CO <sub>2</sub> e/PU)
Glass bottle	400	0.589	0.2350
Plastic cap	3.0	4.4	0.0130
Paper label/adhesive	0.5	1.03	0.0005
Plastic cap wrapping	0.5	2.4	0.0012
Cardboard boxes	47.5	1.03	0.0489
<b>Total</b>			<b>0.2989</b>

from milled apples, each 75 cL bottle contains 1.4 kg of apples, which is 0.105 kg CO<sub>2</sub>e/PU.

This study used a product sold in green bottles, which have the advantage of allowing a higher proportion of recycled glass than for a clear bottle. Data for GHG emissions for glass was obtained from the British Glass Manufacturers Confederation (Enviros, 2003), in which virgin glass and recycled glass have GHG values of 0.843 and 0.529 kg CO<sub>2</sub>e/kg, respectively. A typical recycle rate for green glass is given as 81%, therefore the GHG value for glass is 0.589 kg CO<sub>2</sub>e/kg. The plastic cap is polypropylene, which has a GHG value of 4.4 kg CO<sub>2</sub>e/kg (Plastics Europe, 2005). Minor components of the packaging are also considered, which are the paper label and adhesive, and the plastic wrapping over the cap (assumed to be low density polyethylene). Table 15.2 details the mass and GHG values for each packaging component.

Bottles are packed into cardboard boxes (secondary packaging) in units of 12. A GHG value of 1.03 kg CO<sub>2</sub>e/kg for cardboard was taken from the FEFCO LCA inventory (FEFCO, 2006). Each box weighs 570 g and so the *pro-rata* weight for a one bottle PU is 47.5 g, therefore the GHG value is 0.0489 kg CO<sub>2</sub>e/PU.

#### 15.2.1.2 Manufacture (0.061 kg CO<sub>2</sub>e/PU)

Juice bottling includes the process steps within the dotted line in Fig. 15.3. Estimations were made for the duration of each stage that involves an electric motor, which is required because operation of these stages is intermittent. The thermal processing step is achieved in two water bath pasteurisers. Calculated data for each process step is given in Table 15.3.

**Table 15.3** Electrical energy required for the milling, pressing and pasteurising stages of 1200 bottles of apple juice.

<b>Unit operation</b>	<b>Motor power (kW)</b>	<b>Duration (hours)</b>	<b>Power used (kWh)</b>
Two pasteurisers	7.0	8.0	112.0
Two pumps	0.37	1.0	0.74
Bottle sealer	2.0	2.0	4.0
Pulveriser/mill	3.0	4.0	12.0
Press	1.5	4.0	6.0
Bottle washing machine	3.0	0.5	1.5
High pressure washer	1.0	0.5	0.5
<b>Total</b>			<b>136.74</b>

Total electrical energy required to process 1200 bottles of juice is 136.74 kWh or 0.114 kWh per PU (bottle). Conversion of electrical energy to kg CO<sub>2</sub>e uses the emission factor from Defra (2008), which results in the juice bottling process contributing 0.061 kg CO<sub>2</sub>e/PU. Most of this is from the pasteurisers (thermal processing step).

#### 15.2.1.3 *Transportation (0.057 kg CO<sub>2</sub>e/PU)*

Apples are grown both on the farm and at a nearby farm 12 miles away. Transportation of apples from the trees to the juicing process is by tractor, with the apples packed in large wooden bins. These wooden bins are re-used.

Estimations are made for the distances travelled in delivering the raw materials to the farm, and for the number of journeys made. Table 15.4 presents the breakdown of transportation GHG emissions for the various raw materials.

#### 15.2.1.4 *Waste (0 kg CO<sub>2</sub>e/PU)*

Two categories of waste are generated; waste water from cleaning and washing operations, and apple pulp from milling and pressing.

Waste water is gravity fed to a reed bed, which removes much of the organic matter, and fixes the carbon and nitrogen within the plant material. It is arguable that within the 100-year lifecycle suggested by PAS 2050, all of the organic carbon and nitrogen will end up as gases, and in doing so contribute to GHG emissions.

**Table 15.4** GHG emissions (kg CO<sub>2</sub>e) for transportation of the raw materials used for 75 cL bottles of apple juice.

Component	GHG value (kg CO <sub>2</sub> e/PU)
Wooden bins of apples	0.0092
Glass bottles	0.0243
Plastic caps	0.0122
Cardboard boxes	0.0110
<b>Total</b>	<b>0.0566</b>

This is not considered during this study because no data is available on the quantities of organic materials in the waste water. No caustic or detergents are used for the cleaning operation.

Apple pulp is fed to the pigs that live on the farm, which is a carbon zero activity.

15.2.1.5 *Overall carbon footprint (0.525 kg CO<sub>2</sub>e/PU)*

Table 15.5 compiles the GHG emissions for each of the categories detailed above. The CF for these 75 cL bottles of Cox’s apple juice is 0.525 kg CO<sub>2</sub>e/PU. The most significant component of this footprint is the glass bottles, which makes up 45%, followed by the apples at 20% and the processing at 12%. The pasteurisation step only contributes 10%.

15.2.1.6 *GHG emissions for other food products*

There are now numerous publications freely available on the internet that quote carbon footprint values for food products (Tate & Lyle, British Sugar, Fat Tire Ale). Some of these have used the

**Table 15.5** GHG emissions (kg CO<sub>2</sub>e) for a 75 cL bottle of apple juice.

Category	GHG emissions (kg CO <sub>2</sub> e/PU)
Raw materials	0.407
Manufacture	0.061
Transportation	0.057
Waste	0.000
<b>Total</b>	<b>0.525</b>

**Table 15.6** Summary of GHG emissions for manufactured food products, per kg product and per product unit.

Food product	Kg CO <sub>2</sub> e/kg or L	kg CO <sub>2</sub> e/PU	PU description
Beef cottage pie	7.6	3.3	Single 434.9 g chilled ready meal
White loaf of bread	0.73	0.60	827 g loaf in plastic bag
Packed mild cheddar cheese	9.8	4.9	500 g plastic pack
Cox's apple juice	0.71	0.53	75 cL glass bottle
Chocolate coated cakes	2.5	0.42	165 g packet
Duck in Hoisin sauce	2.0	0.88	Single chilled ready meal (430 g inc. packaging)
Lamb shanks and roasted potatoes	19	25	Single chilled ready meal (1,300 g inc. packaging)
Thai chicken pizza	3.5	1.6	1 pizza (460 g inc. packaging)

procedures defined in PAS 2050, although the source of the calculation procedures is not always clear. Data presented in Table 15.6 was calculated by a group of researchers whose aim was to advise Defra on applying PAS 2050 for food products and their raw materials (Wiltshire *et al.*, 2009).

Food commodities with *low emissions* (<1 kg CO<sub>2</sub>e/kg or L) tended to be crop commodities with high yields and low inputs, for example:

- apples (0.066–0.100) and bottled apple juice (0.71);
- potatoes (0.12–0.16);
- spring onions (0.23);
- animal feed crops (0.0043 to 0.7400);
- carrots (0.35);
- UK conventional tomatoes grown using 'waste' heat (0.39);
- wheat (0.40–0.74);
- onions (0.42–0.59).

These GHG data were used to calculate GHG emissions for manufacture of the food products in Table 15.6 (Wiltshire *et al.*, 2009). Each of these products has a thermal processing step, either for preserving a raw material (e.g. milk for cheese) or as the final cook or process (e.g. bread or beef cottage pie).

Food commodities with *medium emissions* (1–5 kg CO<sub>2</sub>e/kg or L) tended to be high yielding livestock products or manufactured products, for example:



- milk (1.2–1.4 kg CO<sub>2</sub>e/L);
- duck in Hoisin sauce ready meal (2.0);
- chocolate coated cakes (2.5);
- Thai chicken pizza (3.5);
- chicken meat (3.1–4.4);
- duck meat (4.1);
- tea bags (4.1).

Food commodities with *high emissions* (>5 kg CO<sub>2</sub>e/kg or L) tended to be livestock products and highly manufactured foods, for example:

- pig meat (5.5–9.9);
- beef cottage pie ready meal (7.6);
- packed mild cheddar cheese (9.8);
- beef (10–40);
- lamb shanks and roasted potatoes ready meal (19);
- lamb (27–39).

It is clear from the apple juice example, together with the data presented in Table 15.6 and the above examples, that the thermal processing step does not contribute significantly to the carbon footprint. The packaging materials have an influence because of the energy intensive methods for their manufacture, although insignificant if the food product contains materials from a ruminant origin. However, glass and metal packaging, while having relatively high carbon footprints, are environmentally friendly materials in terms of their minimal effect on abiotic resource depletion. This is not the case for plastic packaging that uses oil as its raw material.

As global warming continues to grab the headlines, thermal processing deserves to receive a more favourable press. This can only improve further as the true environmental impact of a food manufacturing operation becomes important, which requires other impact factors to be assessed. The UK and EU are starting to investigate environmental labelling of food products by combining the environmental impact into an ‘omni-label’. These initiatives are in their early stages and it remains to be seen what will appear on packaging labels.

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